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Department of Science and Technology
Ministry of Science and Technology
Government of India

Azadi Ka Amrit Mahotsav

Carbon Capture Utilisation and Storage (CCUS) in India and the UK

December 2022

Disclaimer:

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Contents

Foreword

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The India UK 2030 Roadmap paves the way for the UK and India to explore collaborative partnerships to reach the shared ambitious target of achieving net zero emissions in 2050 and 2070 respectively as signatories to the Paris Agreement. The 2030 roadmap is a commitment to build upon existing bilateral research and forge partnerships that support high quality research and innovation while optimising impacts, and minimising duplication.

Along with renewables-based energy electrification, bioenergy, and hydrogen; Carbon Capture, Utilisation and Storage (CCUS) has a crucial role on the road to net-zero. CCUS technologies is essential to reduce emissions as it can be deployed at scale to decarbonise multiple sectors including those that are labelled "hard to abate" such as heavy industry, transport, and power generation. According to a report of IEA, CCUS has the capacity to contribute to 12% reduction in emissions in the power & industrial sector needed to meet the science-based target of 2°C by 2050. Given its relevance, CCUS is a strategic priority for both UK and India. Both countries seek to develop and deploy CCUS technologies as part of their national commitments to reach net zero and face some similar obstacles The India UK 2030 Roadmap seeks to take forward collaboration and share best practice and low-cost climate appropriate technologies in industrial decarbonisation.

The report is a step in this direction to identify respective capabilities and explore potential areas for joint activity in CCUS. The Natural Environment and Research Council (NERC) of UKRI, together with Engineering and Physical Sciences Research Council (EPSRC) and Economic and Social Research Council (ESRC), partnered with the Department of Science and Technology (DST), Government of India to commission this study to map the capabilities and research landscape of CCUS in the UK and India.

UK and Indian researchers have begun collaborating in recent years via mechanisms such as the global Mission Innovation or Accelerating CCUS Technologies. This report identifies the value of direct collaborative action between the UK and India in CCUS research, and the range of potential areas of collaboration in research between the UK and India that I hope will be established, enabling each country to reach net zero.

Christopher Smith

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आज़ादी का अमृत महोत्सव

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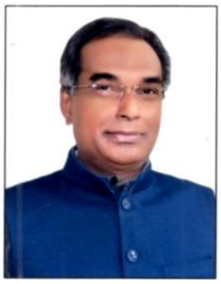
6th September,2022



FOREWORD

India is fast moving to become an economic powerhouse, under the leadership of Hon'ble Prime Minister Shri Narendra Modi, and that the nation is not only on track to achieve the Paris Agreement targets well before time, but also to exceed in very near future. At COP-26 held at Glasgow in 2021, the Hon'ble Prime Minister proposed 'Panchamrit' to deal with the climate challenge, which includes India's commitment to become a net-zero emissions nation by the year 2070.

Carbon Capture, Utilisation and Storage (CCUS) clearly aligns with five of the seventeen Sustainable Development Goals (SDGs), namely, climate action; clean energy; industry, innovation, and infrastructure; responsible consumption and production; and partnerships to achieve the goals. CCUS is one such key pathways to reduce emissions while achieving sustainable development. Therefore, DST is focussing on CCUS, with accent on R&D and capacity building, to evolve negative emission technologies and methodologies to address issues related to high capital costs, safety and logistics.

The establishment of the Indian CO2 Sequestration Applied Research (ICOSAR) Network by DST was one of the earliest developments to initiate research dialogue on CCUS among stakeholders. In 2015, the Conference of Parties (COP)-21 launching Mission Innovation (MI) emerged as another milestone for R&D on CCS technology in India. India became a part of the transnational MI platform, along with other 21 member countries, including UK, for collaborative RD&D on Clean Energy under Innovation Challenge IC#3 focusing on CCUS. In 2018, DST–supported 19 multilateral CCUS collaborative projects under a Joint Funding Opportunity Announcement (FOA) on IC#3 CCUS Mission Innovation to undertake joint Research & Development with member MI countries to identify and prioritise breakthrough technologies in the field of CCUS and value addition.

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DST is also participating in Accelerating CCUS Technologies (ACT) collaborative research programme for adapting the best global practices and for transfer of CCUS technologies from low to high TRLs. Under ACT call 3 DST has supported two ACT Consortia projects with 5 ACT member countries, with UK as one of the consortia members.

DST has recently created two National Centres of Excellence (CoE) in IIT Bombay and JNCASR, Bengaluru in the area of Carbon Capture and Utilisation. The main aim of these CoEs is to map current R&D and innovation activities in CCUS domain, leverage International linkages and to develop network of researchers, industries and stakeholders with coordinated and synergised research between partnering groups and organisations.

India and UK have been collaborating on CCUS though various platforms. This specialized subject-matter report is a compilation of the various national and collaborative activities on CCUS going on in both India and UK which will enable us to reach the net zero goals. This report is a meticulous compilation of the status of RD&D in CCUS in the two countries, and attempts to identify the complementary strengths and gaps between India and UK in CCUS domain. I believe that this Scoping report will facilitate in evolving potential research directions for advancing collaboration between India and UK with complementarity and reciprocity enabling each country to reach their net zero commitments.

(S. Chandrasekhar)

Executive Summary

This report provides an overview and discussion of the CCUS capabilities and research landscape in the UK and India.

Both countries have supported a wide range of research through funding universities, research organisations, and networks, primarily focusing on capture in both countries. There is more of a focus on utilisation in India and storage in the UK. There has been limited research into transport in both countries.

There has also been research by both established companies and SMEs to develop new CCUS technologies, in some cases spun out from academic research. Research by both large and small companies has tended to focus on capture and utilisation technologies, whilst storage and transport has been dominated by large companies with existing CO_2 and gas handling experience, typically Oil and Gas companies.

There is move towards deployment in both countries, with several pilot scale facilities being developed and deployed and the planning of larger projects to be deployed in the near future, particularly in the UK. These larger projects tend to involve major industrial companies, and combine several capture sites in a cluster to make use of shared transport and storage infrastructure facilities.

Government policy and regulation is also supporting CCUS strongly in the UK and is being developed in India, through both wider climate policies such as the government commitments to Net Zero, and those specific to CCUS. This includes regulating CCUS and associated technologies to allow deployment and demonstration, as well as research funding through government bodies to support early-stage research.

Areas for potential collaboration were identified and grouped into actions targeting Capture, Utilisation, Storage and Transport, and cross cutting themes. These areas could include novel CO_2 capture technology R&D, CO_2 geological storage identification and de-risking and CO_2 utilisation technology R&D. This collaboration could be achieved through building links between the existing research networks in both countries, including linking Indian R&D technologies with UK deployment opportunities and UK storage expertise with Indian institutions to build capacity.

1 Introduction

UK Research and Innovation (UKRI) and Department of Science and Technology (DST) in India are aiming to identify emerging research priorities in the area of CCUS and to define priority areas of mutual interest for possible India-United Kingdom (UK) collaboration. This report has been commissioned to support the development of these priorities.

The report is structured into four main sections. Firstly, an Overview of CCUS technologies is provided. Following that, the Findings and Discussion section summarises the research in terms of Capabilities and Research Landscape for both UK and India. At the end of each Countries' section, a subsection summarising key findings is provided. Lastly, the Conclusions section outlines the main collaboration opportunities identified.

This report was not intended to be comprehensive, but aimed to identify the major developments in both the UK and Indian CCUS landscapes, including the major organisations involved in the developing this industry.

The report was compiled through desk-based research into the areas highlighted in the Specification (PS21188) and guided by discussions with the stakeholders. The information was collated into two spreadsheets (one for UK and one for India, Appendix 1), and the report is based on this body of data.

The desk-based research was supported by interviews with leading CCUS specialists. In the UK, Professor Jon Gibbins (University of Sheffield), Professor Peter Styring (University of Sheffield), and Jonathan Pierce (BGS CO_2 Storage Team Lead) were interviewed. Interviews were also held with members of staff at NERC, EPSRC, ESRC, and UKRI.

In India, interviews were held with Dr. Vikram Vishal (Associate Professor, Department of Earth Sciences, IIT Bombay) and Dr. Nimisha Vedanti (Principal Scientist, CSIR-National Geophysical Research Institute NGRI, Hyderabad). To provide more details on the research findings of this report, two spreadsheets (one for UK and one for India, Appendix 1) are also provided for reference with links to the relevant sources. This spreadsheet was developed through desk-based research, with guidance from government stakeholders in both countries.

2 Objectives

This report provides an overview of the development of CCUS and its implementation status in UK and in India. It lays out a broad landscape of the sector in both countries, covering research and development focuses, on-going projects and policy frameworks, as well aspects related to social and environmental impacts and economic feasibility studies. The findings present a clearer view of the CCUS landscape in both countries and the conclusions suggest areas for potential collaboration between the two countries. The key objectives of this report, as defined in the Specification (PS21188) are:

1. To provide a concise overview of the carbon capture, utilisation and storage capability in India and the United Kingdom
2. To produce an overview/map of the Indian and UK CCUS research landscapes to date, including highlighting existing collaborations
3. Identify key opportunities for collaboration in joint research programs between India and the UK

3 CCUS Overview

In order to meet the Paris Agreement goal of limiting the global temperature increase to well below 2°C, and preferably to 1.5°C, when compared to pre-industrial levels, a drastic transformation of industry will be required. Along with renewables-based energy electrification, bioenergy, and hydrogen, CCUS has a crucial role on the pathway to achieve net-zero. A report from IEA estimates that CCUS could provide 12% of the emission reductions in the power & industrial sector needed to meet the science-based target (SBT) 2°C, capturing around 6 gigatons of CO_2 per year in 2050 (IEA, 2020). CCUS has a strategic role in this scenario as alongside the power sector, it could allow emissions reduction in hard-to-decarbonise sectors and even capture of diffuse CO_2 emissions by utilising DAC.

As signatories of the Paris Agreement, UK and India have committed to achieve net-zero, respectively in 2050 and 2070 and both countries acknowledge the importance of CCUS in their strategy to achieve the targets.

In the UK, CCUS technologies are considered one of the key pillars for achieving the net-zero legally binding targets. CCUS is part of the National Industrial Strategy as a tool to decarbonise industry while generating jobs and supporting both the country's levelling-up agenda across different regions and the recovery from the Covid-19 crisis (HM Government, 2021).

A broad policy framework has been developed, establishing the basis for industrial development by establishing a carbon pricing mechanism (UK ETS), regulatory framework for storage (The Storage of Carbon Dioxide (Licensing etc.) Regulations, 2010), and cross-sectorial deals and initiatives (the North Sea Transition Deal (HM Government, 2022) and Clusters definition (Department for Business, E.& I.S., 2022a). With key incentives and the emissions reduction targets in place, the focus is now shifting towards deployment. The UK has been focusing on leveraging existent infrastructure by transforming industrial clusters into CCUS and hydrogen production clusters. Two industrial clusters are expected to be deployed by mid-2020s (HyNet and East Coast Cluster), while a further two are expected by 2030, with the Net Zero Strategy setting out an ambition to capture and store 20-30 $MtCO_2$/y by 2030 (HM Government, 2021).

In India, CCUS has also been identified, as a strategic priority in its second Biennial Update report submitted to the UNFCCC (MoEF, 2012). The DST, India established the Indian CO_2 Sequestration Applied Research (ICOSAR) Network in 2007, as a stepping stone to facilitate CCUS research. CCUS was also seen as a potential climate mitigation solution in the National Action Plan for Climate Change (NAPCC, 2008). In 2015, India added a fresh impetus through participation in the Mission Innovation Challenge at CoP21, focused on CCUS technology and feasibility research. Recent reports from CEEW, India (2021) have estimated significant potential of CCUS in India's energy mix, accounting for 30% of fossil fuel energy as primary energy share in industries, refineries, and other carbon intensive sectors. An additional study (Garg *et al.*, 2017) has also suggested a potential mitigation of 780 $MtCO_2$ at a cost below GBP 46/t CO_2 over the next 30 years through CCUS in India.

However, so far uptake in India has been relatively slow, owing to the high technological cost, limited scalability, incentives and policy interventions. The DST along with the Government of India has been instrumental in exploring opportunities in geological storage capacity, developing carbon capture technologies for fossil-fuel based industries, and supporting the utilisation of CO_2 as a precursor to valuable chemicals and products. Big industries including petrochemicals, steel, and cement have also incorporated CCUS projects into their operations and explored processes such as concrete curing, enhanced oil recovery, and mineralisation. Public sector undertakings (PSUs) are also actively engaged in CCUS pilots across the country.

India has been gaining momentum in CCUS, particularly over the last five years. Early adoption by large enterprises to set up CCUS plants in India has led to greater acceptance and a wider push for research and implementation of CCUS technologies across the value chain. Research and development networks have been specifically established to accelerate the CCUS technology readiness and also understanding the economic and social impact in India.

Both UK and India share the common goal of reducing emissions while undertaking the safe and cost-effective deployment of novel technologies, aligned with each country's development strategy. Technology research and development is an enabler which allows this. The section below aims to provide a brief description of the main technologies under development and these are further mentioned in the report. As this is not intended to be a comprehensive or in-depth technology review, references for further information are provided.

3.1 Capture Technologies

Carbon capture technologies rely mainly on two basic principles, chemical absorption and physical separation. Both constitute the basis of technologies that are well-known in the oil and gas industry for natural gas processing such as amine solvents and solid adsorbents. The technologies focusing on CO_2 removal before combustion are classified as Pre-combustion capture technologies, the most advanced ones, present in the Oil and Gas industry. Post-combustion capture technologies, on the other hand, focus on CO_2 removal from flue gas, where the concentration of CO_2 is lower, a challenge that recent technology developments have been focusing on to overcome in an increasingly efficient manner. Lastly, oxyfuel combustion focuses on modifying the combustion process so that the flue gas has a high concentration of CO_2 to enable an easier separation. These technologies can be further sub-divided depending on the applied separation mechanism:

- Solvents: this is currently the most common technology for capture. Separation occurs via absorption of CO_2 into a solvent, either chemically or physically. Amine-based solvents are the most well-known examples of chemical carbon capture solvents used in industry, and there are several R&D projects aiming at reducing the energy costs related to the regeneration process (Gibbins and Lucquiaud, 2021)

- Solid Adsorbents: CO_2 flows through a bed of packed adsorbents at elevated pressures. The bed is then regenerated either by temperature swing adsorption (TSA) or pressure swing adsorption (PSA) mechanisms (Global CCS Institute, 2021)
- Membranes: CO_2 is separated from other gases by selectively interacting with a membrane, using partial pressure as a driving force (Global CCS Institute, 2021)
- Cryogenic: CO_2 is frozen out of a waste stream, and solid CO_2 of high purity is collected. This requires significant energy to achieve the freezing point. (Mondal, Balsora and Varshney, 2012)
- Solid-looping: involves the use of metal oxide (MeOX) or other compounds, associated with fluidised bed reactors to transfer CO_2 from high-temperature streams from one reactor to another (Global CCS Institute, 2021)

Direct Air Capture (DAC): relies on the use variants of some of the above mentioned technologies such as solid sorbents or solvents, which capture CO_2 directly from the air rather than from flue gas streams (Realmonte et al., 2019).

3.2 Utilisation Technologies

Once the CO_2 has been captured, it can then be used or stored. CO_2 can either be used directly as a product or be used as a feedstock for the production of other chemicals:

Utilisation

- Direct Utilisation
    - Enhanced Oil Recovery (EOR): CO_2 is injected into oil and gas reservoirs to enhance oil recovery. Currently, this is the largest use of externally sourced CO_2 (IEA, 2019b).
    - Others: high purity streams of CO_2 can be used in several other applications such as food manufacture and for healthcare. CO_2 can also be used in other industrial processes as a heat transfer fluid, as a solvent (e.g. for dry cleaning or decaffeination processes), as yield boosters (e.g. for greenhouses or algae production) or welding (IEA, 2019b).

- CO_2 to products:
    - Chemicals and polymers: the main example is urea which is currently the main use of CO_2 that is produced in the ammonia production process. CO_2 can also be converted to monomers for plastics

(polycarbonates) (IEA, 2019b). Routes to chemicals also include microbiological conversion.

- **Fuels Production:** CO_2 is hydrogenated to methanol, which then can be converted into fuels. In the indirect route, CO_2 can be converted to CO (reverse water shift) and then combined with hydrogen via Fischer-Tropsch steps to lead to gasoline, diesel and other fuels (Styring and Dowson, 2021).
- **Mineral carbonates:** CO_2 can be used in the production of building materials as a curing agent or as a raw material in its constituents (cement and construction aggregates). In these applications, CO_2 reacts with calcium or magnesium to form low-energy carbonates (IEA, 2019b).

3.3 Storage & Transport Technologies

- **Storage in depleted oil & gas reservoirs and deep saline formations:** CO_2 can be injected into deep underground/underwater geological formations such as saline aquifers and depleted oil & gas reservoirs. Structural trapping, a key point in geological storage, takes place as the injected fluid is buoyant and rises. Mineralisation also takes place over a long time period (Kelemen et al., 2019).
- **Storage in Basalts and other basic rocks:** the basicity of basalt increases its reactivity with CO_2, allowing mineralisation to take place at a faster rate, however its low permeability makes injection of CO_2 difficult and the structural trapping of CO_2 uncertain. This technology still under development and is at a lower TRL (Kelemen et al., 2019).
- **Unmineable Coal Seams:** CO_2 is captured and injected into unmineable coal seams in combination with enhanced coalbed methane recovery (ECBMR).
- **Transportation:** CO_2 can be transported via pipeline, trucks, rail or ships (Global CCS Institute, 2021).

4 UK Capability Results and Discussion

4.1 UK CCUS Capability Results

This section presents the key findings related to the CCUS capability in the UK. It is not intended to represent a complete coverage of all UK players, but includes the key organisations.

4.1.1 UK Universities Results

University Name	Campus location(s)	Capture	Utilisation	Transport	Storage
University of Sheffield	Sheffield	x	x		
Swansea University	Swansea	x	x		
Imperial College London	London	x	x		x
Nottingham University	Nottingham	x			x
Manchester University	Manchester			x	x
Cranfield University	Cranfield	x	x	x	
Cardiff	Cardiff	x			
Strathclyde	Glasgow	x			x
UCL	London	x			
University of Greenwich	London	x	x		
University of Edinburgh	Edinburgh	x			
University of Cambridge	Cambridge	x	x	x	
Durham University	Durham				x
Newcastle University	Newcastle upon Tyne	x	x		
University of Southampton	Southampton	x	x		
University of Oxford	Oxford	x	x	x	x
London School of Economics	London	x	x	x	x
University of Leeds	Leeds	x			
Heriot Watt	Edinburgh	x	x		x
University of Aberdeen	Aberdeen	x		x	x

This is a summary of Table 1.1 which can be found in the accompanying spreadsheet (Appendix 1, links to each university are also included).

This work identified 20 Universities (Table 1.1) in the UK as leading research into CCUS. This is not a comprehensive list of all UK universities which have recently published on relevant CCUS subjects but represents the most active participants. This research includes the technical and engineering aspects of CCUS, and encompasses research into the economic and policy aspects, and the social and environmental impacts of CCUS technologies, carried out by these universities. The most researched areas at these universities are shown below in Figure 1, with 19 out of the 20 universities studying capture, 11 Utilisation, 10 Storage, and 6 Transport.

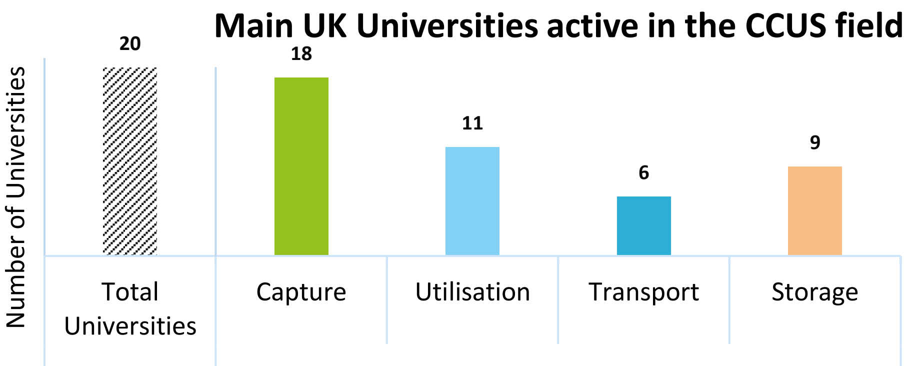


Figure 1: Main UK Universities identified during research. Details about projects and research focus can be found in the accompanying spreadsheet (Appendix 1).

The key UK facility for demonstrator scale CCUS research, is the Pilot Advanced Capture Technology Facilities (PACT) based at the University of Sheffield's Translational Energy Research Centre (TERC). This pilot is capable of capturing up to 1 t/day of CO_2 using conventional amine solvent technology from a variety of emission sources which model commonly found flue gas mixtures, and can be used as a test bed to develop new technologies (University of Sheffield, website accessed April 2022)

There is also a significant pilot demonstration facility at Cranfield University (Gas turbine and combustion plants 50-750 kWth, with capture demonstration facilities for oxy-fuel, amine, and calcium looping technologies and a CO_2 pipeline trial facility). At Imperial College London there is a smaller scale testing facility, although this is primarily for teaching, it can also be used as a test bed using primarily amine-based solvents (Cranfield University, website accessed April 2022; Imperial College London, website accessed April 2022).

4.1.2 UK R&D Institutes Results

There are at least eight research institutions, separate from universities, which also cover CCUS research in the UK (Table 1.2). These are both networks which link universities, and also standalone research institutions.

Institute Name	Campus location(s)	C	U	T	S
British Geological Survey (BGS)	Nottingham, Edinburgh			x	x
Energy Technologies Institute *(Now Closed)*		x		x	x
GeoEnergy Research Centre (GERC)	Nottingham, BGS			x	x
IEAGHG R&D programme	Cheltenham	x	x	x	x
National Oceanography Centre	Southampton				x
National Physical Laboratory (NPL)	Greater London	x	x	x	x
Scottish CCS Centre	British Geological Survey Heriot-Watt University University of Aberdeen University of Edinburgh University of Glasgow	x	x	x	x

	University of Strathclyde				
TWI Ltd	Cambridge		x	x	x
UK CCS RC	University of Sheffield University of Cambridge Imperial College Nottingham BGS University of Edinburgh Manchester Cranfield Cardiff Manchester Strathclyde UCL	x	x	x	x

This is a summary of Table 1.2 which can be found in the accompanying spreadsheet (Appendix 1, links to each university are also included).

The two key networks are the UKCCSRC and the Scottish CCS Centre, which support the coordination of university research into CCUS. The IEA Greenhouse Gas R&D centre, a public private partnership, also commissions and coordinates research into CCUS storage, both within the UK and globally (IEAGHG, website accessed April 2022).

These organisations often have areas of specialist knowledge, which whilst not specific to CCUS, can be applied to the area, and are now publishing or carrying out research in the CCUS area. TWI (The Welding Institute) (Material Science) and National Physical Laboratory (NPL) (Measurement), both have specialism in non-CCUS areas, but are applying their knowledge to CCUS research. The TWI is carrying out research into materials for CCUS systems and the NPL is researching measurement and detection which is particularly applicable to CCUS storage operations (TWI, website accessed April 2022; NPL, 2021).

The British Geological Survey (BGS) is a world leading provider of geoscientific data and has carried out extensive surveys into the potential for storage in the UK and globally, including a previous study in India completed in 2012 (British Geological Survey, website accessed April 2022 a). They are a leading organisation in assessing storage potential at UK subsurface sites, including the CO_2 Stored database, which has identified storage of over 70 billion tonnes of CO_2 (British Geological Survey, website accessed April 2022b) This study was funded by the Energy Technologies Institute (ETI), which closed in 2019. ETI funded and delivered research into a wide range of CCUS technologies to develop an evidence base, through 16 projects, including verification and monitoring of storage and examination of new capture technologies (ETI, website accessed April 2022). BGS is also currently involved in the COMICS programme in India, studying the safety aspects of CO_2 storage, developing an understanding of local storage risks, and creating risk management tools and techniques in the Cambay basin.

The BGS also jointly operates GERC (GeoEngineering Research Centre), with the University of Nottingham, and funded by EPSRC and NERC. This facility provides a range of geoenergy research opportunities, including sub surface gas monitoring and leak detection through the 'Enabling Onshore CO_2 Storage in Europe' research programme (GeoEnergy Research Centre, website accessed April 2022).

UKRI is undertaking a scoping study, led by NERC, to develop a geological storage testbed (research infrastructure) in the UK. This is currently in an early phase of development to scope and refine the capabilities and infrastructure options required to be able to answer science questions and technology challenges that CO2 storage in the UK and internationally pose (British Geological Survey, 2021). The National Oceanography Research Centre has strong links to the University of Southampton and has carried out research focusing on the impact of CCUS storage on the marine environment, including the potential for, monitoring, and impact of leaks. This research has been funded by NERC, including the CHIMNEY and STEMM-CCS projects (National Oceanography Centre, website accessed April 2022).

4.1.3 UK SMEs Results

There are a large number of UK SMEs which are active in CCUS. This study identified 16 of particular interest due to the development of novel technologies or through significant fundraising. These SMEs are predominately spin outs from UK universities and will often maintain their links with the universities.

As shown in Figure 2 below, of these 16 SMEs, 11 were involved with capture, 9 with utilisation, 3 with storage and none were involved with transport. The three SMEs involved in storage are utilising CO_2 to create aggregates, which allows the CO_2 to be stored for a significant period of time through its use phase.

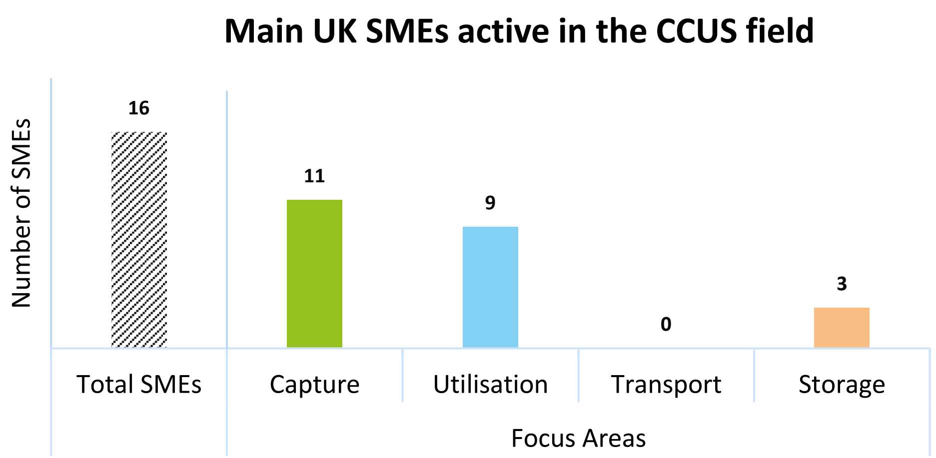


Figure 2: Main UK SMEs identified in the research. More details about technologies and development stage can be found in the accompanying spreadsheet (Appendix 1).

The capture focused SME technologies (Table 1.3) include non-amine solvent capture (C-Capture), adsorbent capture technologies, including Metal Organic Frameworks (MOFs) (MOF Technologies) and polymer adsorbents (PolyCapture), cryogenic capture (PMW Technologies), and capture through carbonation of solids (Carbon8, Origen). Utilisation technologies include functionalisation into polymers (Econic, CCM), and use as aggregates (OCO technologies, Sphera). The companies capturing and using CO_2 in aggregates are also the same companies classified as developing storage technologies, because the CO_2 is trapped in the physical structure that is prepared by the aggregates. This provides longer term storage than other utilisation routes, such as chemicals or e-fuels.

SME research and development has been funded through a range of government programmes, including the BEIS Energy Entrepreneurs Fund, which is now part of the wider Net Zero Innovation Portfolio (NZIP). There has also been funding through specific programmes including the Carbon Capture and Utilisation Demonstration (£20m, which ran until 2019), CCUS Innovation Programme (£24m), which ran from 2018-2021. Currently the CCUS 2.0 Competition with £19.5m of funding is running and applications were submitted in late 2021. This had two separate categories, targeting SMEs at TRL 3-5 (Lot 1) and TRL 6-8 (Lot 2) (Department for Business Energy & Industrial Strategy, 2021a)

Company name	Main location(s)	Description of CCUS capability	C	U	T	S	TRL
Econic	Oxford	Catalysts for CO_2 utilisation to convert it into plastics		x			4
Viridi CO_2	Southampton	CO_2 activation catalysts to support the initial steps in chemical pathways to high value products		x			4
PMW Technologies	Chester	Cryogenic CO_2 capture, primarily targeting shipping and industry	x				5
DeepBranch	Nottingham	CO_2 utilisation growing microbes to produce protein. Running a trial with Drax		x			5
MOF Technologies	Belfast	Carbon capture using Metal Organic Frame works	x				5
Promethean Particles	Nottingham	Carbon capture using Metal Organic Frame works	x				5
Sphera	Durham	Produce a carbon negative aggregate for use in concrete blocks, capturing CO_2 from flue gases		x		x	5
Cambridge Carbon Capture	Cambridge	Capturing CO_2 from waste flues to use in aggregates	x	x			5
PolyCapture	Cambridge, Leicester	Polymer based capture material and system. Spun out of Cambridge and Cranfield	x				6
Carbon8	Nottingham	Carbonation of industrial residues from flue gas to form usable aggregates that can be used in concrete which stores the CO_2	x	x		x	6
CCM	Swindon	Carbon capture and utilisation technology, converting CO_2 waste stream into fertilisers and plastics	x	x			6

C-Capture	Leeds	Non-Amine solvent base capture technology – now working with Drax as part of a biogas trial, aiming for 10000t/day	x				7
Origen	Oxford	Uses Lime based capture and slacking, focused purely on the cement and lime industries. Currently working with Singleton Birch to develop the tech, also demonstrating at Tate and Lyle	x				7
OCO Technologies	Suffolk	Create aggregates from fuel waste using accelerated Carbonation to create the solids, which can then be used in building materials	x	x		x	8
Carbon Clean	London, Mumbai, Chicago, Alicante, Hamburg	Developed a proprietary amine solvent for CO_2 capture (CDR MAX). They have achieved up to 150t/day capture. They are involved in the UK Acorn Cluster and 44 projects total word wide, including 2 in India	x	x			9
Progressive Energy	Gloucester, Liverpool	Project developer of renewable energy projects, including leading the consortium for the HyNet Cluster. They have not developed their own technology, but are combining technologies in the cluster	x	x	x	x	N/A

This is a summary of Table 1.3 which can be found in the accompanying spreadsheet (Appendix 1).

With the exception of Carbon Clean (amine based capture), the other UK SME technologies have not been deployed at scale and are still generally in early demonstrator or pilot scale demonstrations, and many are still at lab scale. Figure 3 shows the relative TRLs that a range of companies have achieved so far.

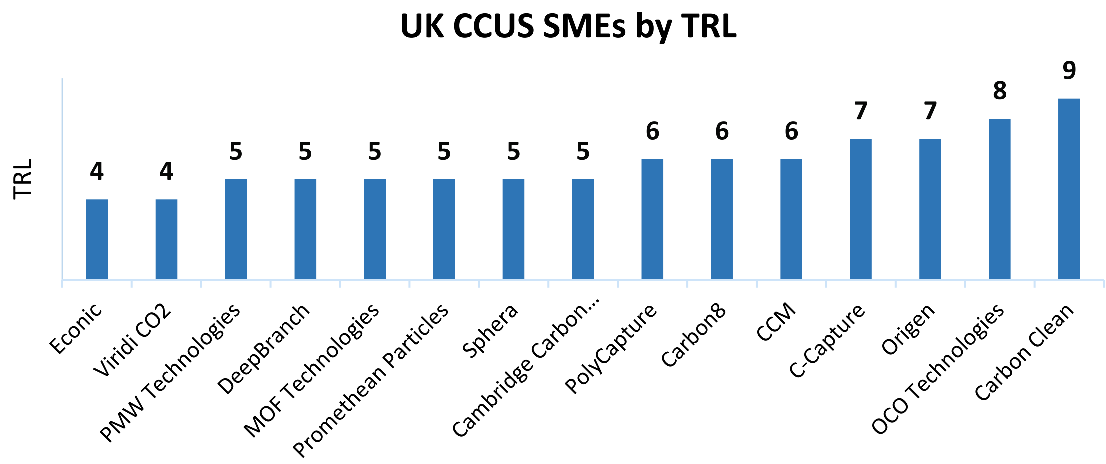


Figure 3: This graph shows the TRLs of UK SMEs in the CCUS landscape. There is a wide range of deployment from these technologies.

The other role in which UK SMEs have acted, is as project developers, for instance Progressive Energy has been one of the leading companies in working to bring together the HyNet Cluster. (This is described in more detail in the UK CCUS Projects Results Section 4.1.5)

4.1.4 UK Large Companies Results

The study identified 12 large companies (Table 1.4) as leading providers of CCUS technologies within the UK, all with existing expertise in either Oil and Gas, Chemical production or handling, or thermal power generation.

The large companies are focused on transport and storage, although some existing Oil and Gas companies have high TRL capture technologies which have not been deployed in the UK but have been deployed in other countries. One example is Shell, which has developed its amine based CanSolv technology and deployed it at sites in the USA, but this has not been deployed in the UK so far. This would need adaption to local regulations and the flue gas at the deployed site, so is not yet at TRL 9 in the UK. (Shell, website accessed April 2022) Another example is Aker, which has major oil and gas systems, but has a division focused on the development of amine capture systems, which have been trialled at the Technology Centre Mongstad, a Norwegian test facility.

Drax, which operates a major biomass power station has provided test locations and facilities for SMEs and large companies to demonstrate their technologies, including C-Capture and Mitsubishi Heavy Industries (MHI).

Company Name	Main Location(s)	Description of CCUS capability	C	U	T	S	TRL
Aker	Aberdeen	Engineering firm with a division focused on Carbon Capture explicitly. Built on amine technology	x	x			7
bp	Norther Endurance Partnership	Lead operator of the Northern endurance partnership and responsible for some of the storage and transport aspects of this	x		x	x	9
Drax	Selby, North Yorkshire	Drax have two pilot facilities at Drax Power Station which is fired by biomass. The first utilises C-Capture's Technology (University of Leeds Spin out) which is aiming to capture 1t/day. This launched in 2019 The second pilot at the plant uses MHI's KS-1 (proven) and KS -21 Solvents (novel) and will capture 300kg/ day. This pilot launched in 2020	x				8-9
ENI	Part of the HyNet Cluster	Responsible for the transport and storage of CO_2 from the HyNet Project			x	x	7
Equinor	Norther Endurance Partnership	Equinor are supporting the storage aspects of the East coast cluster through this programme, including being on the joint licences for the storage			x	x	9
Johnson Matthey	London	Primarily focused on Blue hydrogen Capture, from reforming, can achieve 95%+ capture	x				8
Kellas	East Coast Cluster	Kellas are a major natural gas distribution company, owning and operating pipelines, now looking to enter the CO_2 market			x		9
Mitsubishi	Selby, North Yorkshire	Demonstrating their Amine Solvent CCUS at the Drax site	x				7
National Grid	East coast cluster	Developing the onshore pipelines for the clusters due to existing pipeline know how			x		
Shell	Acorn, East Coast Cluster, SWIC	Taking part in 3 of the UK clusters, as well as developing their own amine solvent (CanSolv) which they have deployed at a plant in the US. Also involved in a major storage trial (Northern Lights) in Norway	x		x	x	9
Tata Chemicals	Northwich	Have installed CO_2 capture technology on a Combined heat and power plant at their Northwich facility, are using the CO_2 in the production of Sodium Bicarbonate	x	x			9
Total Energies	Northern Endurance Partnership	Part of the consortium, providing some technical support to the development of the network. Also building on lessons learned from the Northern lights project			x	x	9

This is a summary of Table 1.4 which can be found in the accompanying spreadsheet (Appendix 1).

4.1.5 UK CCUS Projects Results

There has been limited commercial deployment of CCUS so far in the UK although there are significant government plans to deploy further CCUS technologies in the UK through four UK clusters before 2030. The clusters will be focused on both hydrogen (initially primarily blue hydrogen) and CCUS. Each cluster will contain multiple carbon capture projects, sharing transport and storage infrastructure.(Department for Business Energy & Industrial Strategy, 2021b)

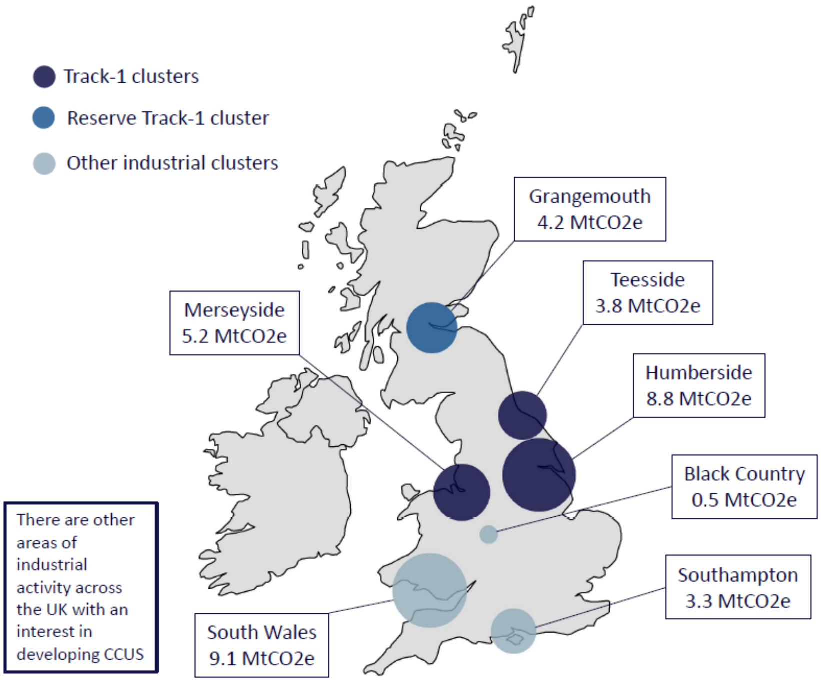


Figure 4: Map of major UK industrial cluster emissions from large point sources (2019). Source: Capturing Carbon and a Global Opportunity CCUS Investor Roadmap, 2022

The four leading clusters (HyNet (Merseyside), East Coast Cluster (Humberside and Teesside), Acorn (Grangemouth), and SWIC (South Wales)) (Figure 4) are planned to be deployed in 2 phases, with support from the government to integrate technology into local high carbon industries. HyNet and the East Coast Cluster were selected for the first phase of projects to be deployed by 2025. They have received government support to develop and applications have recently been submitted by the individual projects that could be included in the clusters (Department for Business, 2022). The projects which are being considered for inclusion are a across a range of industries: Power Generation, Blue Hydrogen production, and Industrial Carbon Capture projects in the biofuels, cement and lime, glass and fertilisers sectors.

By 2030, HyNet is targeting storage of 10Mt/year and the East Coast Cluster is targeting 27Mt/year of CO_2 storage. SWIC (South Wales Industrial Cluster) and Acorn (Grangemouth and St Fergus) are planned to be deployed as phase 2 of the cluster programme by 2030 under current policy. (Department for Business Energy & Industrial Strategy, 2021b)

The clusters are predominately consortia of established, large companies (Table 1.5), although in the case of HyNet (Progressive Energy) and Acorn (Storegga), the clusters are coordinated by SMEs as project leaders, but they are not technology developers themselves.

There is only one operational commercial CCUS project in the UK, capturing 40,000 t/year from an onsite CHP plant at the Tata Chemicals plant at Northwich, with the CO_2 being used in the production of sodium bicarbonate. This uses Pentair Union amine technology. (Tata Chemicals, website accessed April 2022)

There is also an operational pilot plant at Drax, which is used to trial new technologies, as part of Drax's research into BECCS. There have been ongoing trials with MHI to understand the performance of a new amine based solvent (300 kg/day) and C-Capture to understand a non-amine solvent (1 t/day). The MHI trial was sufficiently successful that Drax have signed a contract to utilise the solvent with a target deployment date of 2027 (Drax, 2019, 2021, no date, 2020).

Project name	Main location(s)	Leading participants	Description of project	Project status and Capture Target
HyNet	Liverpool	Progressive Energy Eni UK Essar Oil UK Cadent Inovyn CF Fertiliser Hanson UK University of Chester	One of the Track one selected clusters designed to come online in 2025. From 2025, HyNet is aiming to produce blue hydrogen in the Northwest of England, as well as capturing CO_2 from industry in the region. The CO_2 will then be transported and stored in the region	Development (FID 2022/3) Up to 10Mt/year by 2030
East Coast Cluster	Teesside Humberside	BP ENI Equinor National Grid Shell Total Energies	A combination of Net Zero Teesside, ZeroCarbon Humber, (Two Net zero industrial clusters) and Norther endurance, a storage location in the north sea). This is the second track one cluster for UK CCUS	Development (FID 2022/3) Up to 27 Mt/year
Acorn	Grangemouth, Aberdeenshire	Storegga Shell Harbour Energy North Sea Midstream Partners	Selected as the reserve for Track Clusters for the UK, and likely to be selected in Track 2. This is based in Grangemouth and will focus on collection from a refinery and natural gas site	Development (FID 2025<) 5-10 Mt/year (by 2030)
South Wales Industrial	South Wales	Costain	Cluster targeting decarbonising the south coast of Wales, focusing on the heavy industry located there. Faces a major challenge	Development (FID 2022/3) 16 Mt/year

Cluster (SWIC)			because there is no storage directly adjacent to the location	
Tata Chemicals	Northwich	Tata Chemicals, Pent Air Union	Tata Chemicals installed a Pentair-Union CC technology on their on site CHP plant, and are using the captured CO_2 for manufacture of the Sodium bicarbonate	Operational (2019) 40 kt/year

This is a summary of Table 1.5 which can be found in the accompanying spreadsheet (Appendix 1).

4.1.6 UK CCUS Technologies Results

Due to the limited number of CCUS installations in the UK, only two CCUS specific technologies have been deployed at scale: amine based solvent capture and membrane separation of CO_2 from biogas. There is extensive research happening across a range of other technologies, primarily in the capture sector (Table 1.6). Some capture technologies have been deployed commercially internationally, but not yet in the UK. The UK has been more focused on the development of capture and storage and longer term utilisation, rather than short term utilisation.

4.1.6.1 Capture

There are at least 9 categories of carbon capture technology which are being developed, although there are often many subcategories of technology, or research into the improvement of components of already established technologies.

The capture technology areas with the greatest volumes of research by both academic and commercial organisation are amines solvents, CO_2 sorbents and CO_2 mineralisation. Both academic and commercial organisations are also focusing on DAC which utilises the same methods of capture, but with different technologies. Academic research has also focused on storage monitoring technologies. Large companies and SMEs have placed a greater focus on utilisation of CO_2 than academic research, targeting the production of a range of products, primarily aggregates and bio-utilisation.

The early stage technologies that have ongoing research, are novel sorbents, non-amine solvents, cryogenic capture and metal carbonates. Novel sorbents include MOFs, and polymer technologies which are both currently undergoing demonstrator scale trials in the UK. MOFs have significant research with funded research projects from UKCCSRC and ACT. There are also spin out companies which have been formed to commercialise this technology in the UK including MOF Technologies (spun out of University of Belfast) and Promethean Particles, (University of Nottingham). Polymer capture technologies are being developed by PolyCapture (Cranfield, University of Cambridge).

There is also interest in developing non-amine solvents, which offer lower energy performance than amine technologies. These are being developed by companies including Carbon Clean.

Metal carbonate capture is being developed for both point source and DAC. For point sources, companies such as Origen will regenerate the carbonate, the technology is being installed as pilot plants at a Singleton Birch, and Tate & Lyle. The technology is also being developed for uses in DAC plants, using the same capture cycle, but with reaction with the air (Samari et al., 2020).

4.1.6.2 Utilisation

CO_2 mineralisation is also being developed as a joint capture, utilisation and storage technology. CO_2 is captured as a material which can be formed into an aggregate, to be used in construction. This provides both capture and longer duration storage of CO_2. This technology has been demonstrated by Carbon 8, OCO, Sphera, and Cambridge Carbon Capture, at around TRL 6, with pilot plants being deployed. There appears to be relatively less academic research in this area.

Utilisation technologies, outside aggregate production are relatively less developed in the UK, due to a wider national focus on storage of CO_2. The other utilisation technologies which are being developed in the UK are conversion to chemicals, including polymers and Sustainable Aviation Fuel (SAF), aviation fuels developed from captured CO_2, and biological utilisation, using algae to capture the CO_2 and process it into useful products.

4.1.6.3 Storage and Transportation

Storage and Transportation of CO_2 are mature technologies globally due to its use as an industrial gas. CO_2 is already transported extensively via pipeline and through other methods, including ship, rail and road due to its use as a major industrial gas. Much of the development has been driven by EOR, which requires the same technology to inject CO_2 as storage. This technology is not currently used in the UK.

The key areas for early stage CO_2 storage technology research are monitoring the behaviour of CO_2 within the well and ensuring that it remains in the storage location. Whilst this can be achieved with traditional seismic studies, new technologies, including quantum-based gravity monitoring of storage (University of Birmingham) and drone based monitoring (National Oceanography Centre) research is being carried out in the UK. These are both at very early TRLs.

UKRI is in the early stages of scoping a novel Geological storage testbed (research infrastructure) for CO_2 storage technologies.

CO_2 transport by pipeline is a highly established technology and has been shown to be possible in existing pipelines, including research by DNV GL in 2019, focusing on the safety of reusing natural gas pipelines for CO_2. There is limited additional research into pipeline transport technologies for CO_2, although there is some modelling work on the precise flow behaviours within the pipelines being carried out (Imperial College London, as part of ACT3). There is also some research into the materials for building pipelines for CO_2 transport, via the Forge project, funded by EU Horizon. The UK participant in this work is through TWI, which is supporting the development of early stage materials (ACT, website accessed April 2022).

There is also research into increasing the scale of transport of CO_2 by ship, including a 2018 study funded by BEIS, and led by Element Energy, and a review paper published by Cranfield university in 2021, funded by EPSRC (al Baroudi *et al.*, 2021). CO_2 is currently transported by ship on a small scale (c.1000 t) within Europe, but there have been recent proposals to build significantly larger ships.(Department for Business Energy & Industrial Strategy, 2018) The technology is being developed to transport CO_2 from capture locations which are not close to suitable storage sites. This includes the South Wales Cluster in the UK, which is examining the feasibility compared to the construction of a pipeline. This is currently viewed to be at TRL 5.(TWI, website accessed April 2022)(SWIC, 2022)

Technology Type	Technology name	Leading participants	TRL
Carbon Capture	MOF(Metal-Organic Frameworks)	MOF Technologies	4-5
Carbon Capture	Cryogenic	PMW Technologies	4
Carbon Capture	Polymer Adsorbent	PolyCapture	6
Carbon Capture	Oxy-Fuel	8rivers/ NetPower	6
Carbon Capture	Advanced Amine	Mitsubishi	7
Carbon Capture	Non-ammine solvents	Carbon Clean	7
Carbon Capture	Metal carbonate solids	Origen	7
Carbon Capture	Direct Air Capture (DAC)	Storegga, Carbon Engineering	7
Carbon Capture	Traditional Amine Solvent	Shell, Fluor, Aker Solutions	9
Carbon Capture	Polymeric Membranes	MTR	9
Carbon Utilisation	Biological Conversion of CO_2	DeepBranch	1-6
Carbon Utilisation	Chemical conversion to chemicals and fuels	Econic, Viridi CO_2, CCM Technologies	4-7
Carbon Utilisation	Mineral carbonation	Carbon 8	7
Carbon Utilisation	Enhanced oil recovery (EOR)	BP, Shell	8
Carbon Utilisation	Direct CO_2 utilisation	Tata Chemicals	9
Storage	Storage in Saline formations	BP, Shell	8

Storage	Depleted oils and gas reservoirs	Eni UK	8
Transport	Shipping	Praxair	3-9
Transport	Rail		7-9
Transport	Pipeline	TWI	8-9
Transport	Truck		8-9

This is a summary of Table 1.6 which can be found in the accompanying spreadsheet (Appendix 1).

4.1.7 UK CCUS Policy and Regulation Landscape Results

There has been a significant development in terms of policies and regulations regarding CCUS in the UK in recent years. As part of this research, 23 policy framework documents have been identified, with publishing dates ranging from 2017 to 2022. Most of the policies (13 out of the 23 identified) have been published in the last two years, after the government assumed the legal duty to achieve Net Zero (amendment of the Climate Change Act in 2019) and set out their ambition through the publication of the Ten Point Plan (2020) and the Net Zero Strategy (2021). The policy framework is broad and quite detailed. Most of the documents cover different sectors but with a specific focus on CCUS. The most relevant and latest documents are listed in Table 1.7.

Framework type	Policy or regulatory instrument name	Owning/ administering organisation name	Publication Year
Incentives/ Funding	CCUS Cluster Sequencing	BEIS	Nov-21
	North Sea Transition Deal	BEIS	Mar-21
	Carbon Capture, Usage and Storage: An update on the business model for Transport and Storage	BEIS	Dec-20
	Industrial Energy Transformation Fund	BEIS	Jul-19
	Design of the Carbon Capture and Storage (CCS) Infrastructure Fund	BEIS	May-21
	Net Zero Innovation Portfolio, including CCUS Innovation competition 2.0	BEIS	May-21
	UK Infrastructure Bank	UK Infrastructure Bank	Jun-21
	Industrial Decarbonisation Challenge (IDC)	UKRI	
	Clean Steel Fund	BEIS	Aug-19
Regulatory/Standards	UK Emissions Trading Scheme markets (UK ETS)	BEIS	Jan-21
	The Storage of Carbon Dioxide (Licensing etc.) Regulations	Oil and Gas authority	2010

	Re-use of Oil and Gas Assets for Carbon Capture Usage and Storage Projects	BEIS	2019
	Climate Change Act 2008 Amendment		
Sector Strategy	Net Zero Strategy	BEIS	Oct-21
	UK Hydrogen Strategy	BEIS	Aug-21
	Green Jobs Taskforce	BEIS and DfE	2020
	CCUS supply chains roadmap	BEIS	May-21
	Industry Decarbonization Strategy	BEIS	Mar-21
	The ten-point plan for a green industrial revolution	BEIS	Nov-20
	National Infrastructure Strategy	HM Treasury	2020
	Delivering Clean Growth: CCUS Cost Challenge Taskforce report	BEIS	2018
	The UK CCUS Deployment Pathway	BEIS	2018
	Clean Growth Strategy	BEIS	2017

This is a summary of Table 1.7 which can be found in the accompanying spreadsheet (Appendix 1, links to each document are also included). Source: UK Government official websites.

The identified policy frameworks have been divided into three main categories: (1) Sector strategy – composed of documents expressing objectives and high-level action plans; (2) Incentives/Funding – including mechanisms to incentivise innovation and deployment through grants and/or financing methods; (3) Regulatory/Standards – that includes legal obligations and standards. The documents focus on areas necessary for CCUS deployment including Carbon Pricing, CO_2 Storage Regulation, Infrastructure Deployment Funding as well as Innovation incentives and broader sector deals such as business models/revenue mechanisms to incentivise the development of the value chain.

A central point in terms of policy has been the sequencing and selection of industrial clusters. The cluster sites will become decarbonisation hubs by combining carbon capture, utilisation and storage projects, while leveraging existing infrastructure and driving economies of scale. Besides fostering multi-stakeholder collaboration (Mete *et al.*, 2021), the clusters are also expected to become centres for green jobs as well as for blue hydrogen production, another key enabler of decarbonisation for hard to electrify industries highlighted in the UK Hydrogen Strategy 2021. The initiative is aligned with the government levelling up agenda and also with the broader strategy for building back from Covid-19 impacts. Supporting the demonstration and deployment of relevant technologies has also been a key point, addressed by the Industrial Energy Transformation Fund (IETF) and several UKRI and BEIS innovation initiatives.

In terms of social impact and social barriers, the research identified fewer documents, mainly addressing the social acceptance of CCUS technologies. Overall, a public dialogue study indicated that the UK population recognises the role of CCUS in the path to achieving net-zero, although public knowledge was limited, as 54% said they never heard the term before in March 2020. Public acceptance is subject to safety concerns on leakages as well as impact on marine life with only a small group strongly opposed to it, seeing it as an excuse to continue exploring fossil fuels (Traverse, 2021).

Regarding skills development, the research found study initiatives mapping the CCUS potential impacts in terms of jobs and skills demand such as The Green Jobs Taskforce 2020, which set out the direction for a cross-sectorial discussions to address the topic. The topic is also a core aspect of the North Sea Deal that will publish a more detailed People and Skills Plan (PS& SP) in Q2 2022. The initiative is being led by OPITO, a skills body for the energy industry and it aims at leveraging the established strengths from Oil and Gas while also providing reskilling.

4.1.8 UK TEA & LCA Results

The UK governments, universities, and industry bodies have published research into the costs, opportunities and life cycle of CCUS (Table 1.8). The TEA examine the potential for the installation of CCUS facilities and the potential technologies, whilst the LCA considers the impact of the projects over their complete life time, including a wide range of factors, energy requirements, CO_2 sequestration, and wider impacts on the environment, biodiversity and human health. Private companies planning to develop projects, such as the clusters, in the UK will also carry out TEA and LCA but these are not publicly available.

A key area of published academic research is ensuring consistency in both LCA and TEA methodologies. TEA and LCA studies are not always comparable between projects due to the differences in the methodologies used. Two key papers published by European collaborations focused on developing clear guidelines for projects so that clear comparisons can be made between projects and can ensure consistency within wider assessments. (Müller *et al.*, 2020; Zimmermann *et al.*, 2020) These were funded as part of a European Climate-KIC programme, and were contributed to by authors at the University of Sheffield. Similar studies have also been published by Cranfield, funded by NERC, similarly harmonising previous LCA for greenhouse gas removal.

The UK government has also published papers to understand the potential economic impact of CCUS on the UK Economy and the potential business models for the different parts of the CCUS value chain. These include a BEIS publications: 'CCUS supply chains, a road map to maximise the UK's potential' (BEIS 2021) and 'Carbon Capture and Storage Business models' (2019, updates 2020-2022), which examine the potential operational models for the UK CCUS markets and opportunities for business to come together to develop financially viable projects. Scottish Enterprise have also commissioned their own study from Vivid Economics 'CCUS Economics Impacts Study: Delivering a roadmap for growth and emissions reductions for Scotland' (Vivid Economics, 2021) covering the wider impacts of CCUS on the Scottish economy, through four different growth models.

Industry bodies for the CCUS industry and Oil and Gas industry have published favourable assessments of the economic benefits from deploying CCUS at scale. The OGCI published "The Potential Value of CCUS to the UK Economy" (OGCI, 2018) and the CCS Association, the industry body for UK CCUS, commissioned Cambridge Econometrics to prepare

‘Economic Analysis of UK CCUS’ to cover the impacts of deploying CCUS under different government strategies (Cambridge Econometrics and AFRY, 2021).

The environmental impact and potential impacts of CCUS have also been studied, adding further factors beyond economic costs and benefits. The National Oceanographic Institute, funded by NERC, has carried out research into the impact of CCUS leaks which may occur and what impacts this could have on marine wildlife. The University of Aberdeen has also published an in-depth review of this (Turrell *et al.*, 2022). The Energy Research Partnership has also published “The Environmental Constrains of Net-Zero” which studies the potential wider environmental impacts, including on water and the potential impacts of amine and nitrosamine emissions from CCUS facilities (The Energy Research Partnership, 2021).

Title	Lead Author	Year
Harmonising and Upgrading GREENhouse gas removal (GGR) consequential Life Cycle Assessment	Cranfield University	2017-21
Techno-economic feasibility assessment of CO 2 capture from coal-fired power plants using molecularly imprinted polymer	Dawid P. Hanak⁎, Vasilije Manovic, Cranfield	2017
The Potential Value of CCUS to the UK Economy	OGCI	2018
Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology	Wood (for BEIS)	2018
Vivid Economics: Energy Innovation needs Assessment	Vivid Economics	2019
Carbon Capture, Usage and Storage An update on business models for Carbon Capture, Usage and Storage	BEIS	2020
Techno-economic assessment guidelines for CO_2 Utilisation	A.W. Zimmermann et al., University of Sheffield	2020
Advances and challenges of Life Cycle Assessment (LCA) of Greenhouse Gas Removal Technologies to Fight Climate Changes	P. Goglioa,b*, A. Williamsb, N. Balta-Ozkanb, N.R.P. Harrisb, P. Williamsonc, D. Huisinghd, Z. Zhange, M. Tavoni	2020
Updates on the industrial carbon capture and dispatchable power agreement business models	BEIS	2021
CCUS Supply Chains: a roadmap to maximise the UK’s potential	BEIS	2021
CCUS Economics Impacts Study Delivering a roadmap for growth and emissions reductions for Scotland	Element Energy, Vivid Economics	2021
Techno-economic portfolio assessment and optimisation tool for CO_2 transport and storage and guidelines for the development of flexible CCS networks	Zhenggang Nie	2021

Economic Analysis Of UK CCUS	Cambridge Economics, AFRY for CCSA	2021
Analytical review of life-cycle environmental impacts of carbon capture and Utilisation technologies	Garcia-Garcia, G., Fernandez, M.C., Armstrong, K.	2021
The Environmental Constrains of Net-Zero	Energy Research Partnership	2021
CCUS Development Pathway for the EfW Sector	Andrew Coulthurst, Leyla Lugal, Kat Rowland	2021
Post-combustion carbon dioxide capture : best available techniques (BAT)	Environmental Agency	2021
CCUS: Transport and Storage Business models	BEIS	2022
Next Generation Carbon Capture Technology – Technoeconomic Methodology Report	AECOM	2022

This is a summary of Table 1.8 which can be found in the accompanying spreadsheet (Appendix 1)

4.1.9 UK Stakeholders Map

There are a wide range of stakeholders in the UK CCUS landscape, with significant overlaps between the key groups. There is a highly complex set of linkages between the stakeholders, especially within the clusters, where almost all mapped stakeholders will be involved. The key roles of all the stakeholders are explored in more detail in their relevant sections in this part of the report.

The direct assessments of the key stakeholders have primarily been carried out by the CCUS clusters in the UK as part of the cluster development process. This has been required to gain a clear view of the needs of the area and gain the social acceptance of the project. These reports have not been combined for all the clusters and are not publicly available which makes it difficult to assess, however summaries have been posted on the cluster websites.

The stakeholders map shown in Figure 5 shows the stakeholders involved in CCUS projects and the stakeholders are drawn from the groups which are directly involved in the development of CCUS technologies and groups impacted by them.

This includes the companies directly involved in the production of CCUS technologies and the development of projects, the companies that are currently emitting carbon, and the organisations that will finance the projects, and insure the risk of CO_2 leakage.

There are also the government stakeholders who are important to industry due to the early stage of CCUS development. This includes the licensing and rights of storage locations, financial, policy and regulatory support for the projects, and the funding of research and innovation. This also includes the environmental impact of projects and the associated regulations. The universities and research organisations interact strongly with this pillar, developing new technologies and providing academic support to both governmental policy and also to the commercial assessment of projects and development of technologies.

The community stakeholders are also impacted through the deployment of CCUS, through both environmental impacts, as well as through economic development of jobs.

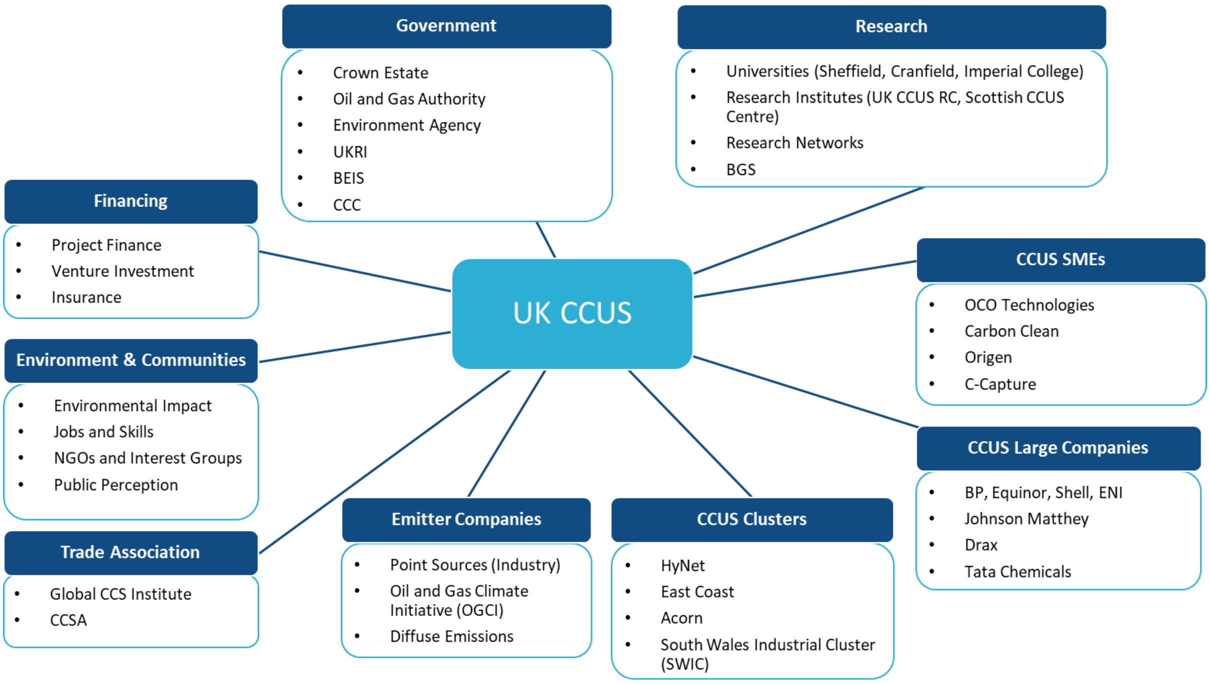


Figure 5: UK Stakeholders map active in the CCUS space. It is not a comprehensive description of all stakeholders involved. Please refer to the accompanying spreadsheet (Appendix 1) for more details.

4.2 UK CCUS Capability Discussion and Insights

4.2.1 UK Universities Discussion

The UK has a complex research landscape for CCUS, and this report identified the leading universities involved through the UKCCSRC and SCCS, alongside 5 other universities with strong links to CCUS either through start-ups or policy research. The UKCCSRC and SCCS Centre lead domestic funding of CCUS and have established programmes to co-ordinate and link research topics. Outside of these programmes there is also wider funding available, particularly in social, environmental and policy research which is often part of wider climate change or environmental institutes such as the Oxford Smith School. There are also international collaborations, such as ACT which UK universities have contributed significantly to.

The universities have built on existing expertise, developed through previous research, such as the extensive O&G research at universities including Strathclyde, to focus on CCUS as a future area. The universities have also been able to develop facilities and core research clusters, such as PACT at the University of Sheffield, to enable the larger stage trialling of new technologies, and the refinement of existing technologies. There is also the potential for the development of new facilities which would be strongly linked to Universities, such as the UKRI Geological storage testbed (research infrastructure), which would offer a wide range of scientific benefits, by providing a leading facility for the research and demonstration in CO_2 storage.(British Geological Survey, 2021)

The presence of demonstration and scale up facilities has supported technologies to grow from bench top to larger scale, which has facilitated spinouts from universities, including C-Capture (University of Leeds), PolyCapture (Cranfield University and University of Cambridge), and Carbon8 (University of Greenwich). These spin outs will then produce their own further research, often maintaining ongoing links with the universities.

The areas of research at universities have broadly aligned with the key areas of industrial development in the UK, primarily focusing on the capture, with some focus on the monitoring of storage. There has been less on transport of CO_2, a mature technology, and on utilisation which has less emphasis more broadly in the UK.

Most research is early stage and bench top based, covering fundamental aspects, or is desk based, covering either the financial and social aspects of CCUS. There are opportunities for large trials and experiments of later TRL technologies through facilities such as PACT at Sheffield, and there has also been scale up of research through spin outs.

There is also significant research carried out outside universities through private companies, developing their own technologies as commercial products, these are covered in more detail in the following section.

4.2.2 UK R&D Institutes Discussion

UK R&D institutes play a range of important roles alongside universities in UK CCUS research either as subject area experts within research, such as the British Geological Survey, National Physical Laboratory, National Oceanography Centre, and TWI, or as research co-ordinators and communicators, including UKCCSRC, SCCS Centre, and the IEAGHG R&D programme.

The specialist knowledge enables the development of research focused in dedicated areas. The BGS is a globally leading authority on geological storage and has lead major studies both in the UK and internationally into storage capacity, including in India, and provides the potential for supporting new and existing research facilities in storage, such as the existing GERC, and the proposed UKRI Geological storage testbed (research infrastructure). The National Oceanography Centre also provides similar marine expertise, allowing CCUS research in the UK to build on existing strengths within the academic field and leverage previous funding. Their storage monitoring work includes further development of existing seismic technologies, as well as the inclusion of advanced quantum and drone-based technologies (UKCCSRC, no date).

The research co-ordination and communication institutes provide important forums for academics to interact and share research, as well as opportunities to identify areas of future research, or current limitations. These are discussed in the research networks section.

4.2.3 UK SMEs Discussion

SMEs are more prevalent in the carbon capture, and utilisation sectors because these have the greatest opportunities for innovation and lower barriers to entry, compared to the established and mature transport and storage sectors, which have higher capital costs to entry. Although globally, large companies have rolled out carbon capture technologies, predominately amines, at scale, these technologies are highly energy intensive and there is a significant drive to find alternative routes to capture. SMEs are working across a wide range of technologies, often at a relatively small scale initially, but are carrying out extensive private R&D to bring this to market

The SMEs in the UK tend to be spun out from UK university research, and many maintain links to the university to support research or through access to facilities that would otherwise be difficult to access, including the potential for pilots and demonstration. The other routes to demonstration of technologies is through partnering with large companies in foundation industries which are looking to decarbonise, such as Origen partnering with Singleton Birch, to decarbonise lime production. The collaboration with large companies for SMEs is also key for storage, because SMEs are likely to require access to storage networks and facilities due to the very high capital costs of developing them, so will be dependent on external networks.

Utilisation is one of the few alternatives to this, either through the production of a valuable product in the capture process, or through the utilisation of captured CO_2. Utilisation is being researched more in SMEs than at universities, particularly through the production of aggregates (OCO, Sphera, Carbon8), which provide an addition revenue stream compared to pure capture and can improve the economics of capture process, opposed to pure storage.

4.2.4 UK Large Companies Discussion

Large companies, normally Oil and Gas companies, particularly dominate the transport and storage aspects of the UK CCUS industry. These large companies are often in the sector due to their existing technical know-how including, carbon capture technologies, CO_2 transport knowledge, and their subsurface gas handling ability for storage. The companies also have access to significant capital required to fund and deploy these projects on a large scale or can reuse existing infrastructure which was previously developed during O&G extraction. This has also led to the relative lack of SMEs targeting these aspects of CCUS.

The large oil and gas companies have experience in handling CO_2 due to its industrial uses in many existing products. The technologies that they have developed have not been deployed in the UK at large scale yet, and would need adaption to local geology and regulation, but have been commercially or near commercially deployed in other countries, providing initial knowhow. Large oil companies also have experience of storing CO_2, through its use in EOR (Enhanced Oil recovery), which is the current largest uses of CO_2 (IEA, 2019b), although this is not used in the UK. Large companies also provide funding and carry out research to develop their own technologies (Aker) as well providing locations for SMEs to trial technologies, such as Drax.

4.2.5 UK CCUS Projects Discussion

The major projects in the CCUS sector in the UK are currently dominated by large, international companies, often from the oil and gas sectors. HyNet, one of two clusters chosen in 2021 in the first round of funding is led by Progressive Energy, an SME, but has significant backing from Eni and includes ESSAR and Tata Chemicals as lead partners. The other funded cluster, the East Coast Cluster, focused on Teesside and the Humber, includes BP, Shell, Total Energies, Equinor, and Eni in its lead team. (East Coast Cluster, no date) (HyNet, no date)

The clusters are receiving significant backing from government to drive the development of these sites and generate the initial conditions for future CO_2 storage development. This support is also providing research opportunities to both academics and SMEs because the development of the clusters will allow access to storage facilities for SMEs, and greater data for academic study of the process.

The cluster also are beginning to incorporate early stage technologies and provide the key storage infrastructure that SMEs would not be able to develop on their own. There is also the incorporation of new technologies to these sites, such as the Acorn Cluster partnering with Carbon Engineering to potentially incorporate DAC facility into the network (ACORN, website accessed April 2022).

4.2.6 UK CCUS Technologies Discussion

Many technologies that are mature globally have not yet been deployed at scale in the UK, in particular storage and transport which are already at a high TRL because they have been used in the past for EOR. This is also supported by the reuse of existing infrastructure, so there is limited development of the technologies themselves within the UK. These technologies may need some modification to work correctly with the exact local geology that they will be used in. The UK has extensive experience in appraising storage opportunities through the BGS and other research, so should be able to adapt these technologies to local geology.

The area of monitoring CO_2 storage is significantly newer and covers both the development of existing technologies and the creation of new early stage technologies. This development allows for lower cost and more frequent monitoring than traditional seismic surveys which are currently used. This monitoring will be key for ensuring that the storage is effective, and that the CO_2 will remain stored as part of the environmental and social acceptance of CCUS. The modelling and monitoring of CO_2 storage is being developed rapidly, and UKRI's Geological storage testbed (research infrastructure) will add to this capability, by providing a bespoke testing and demonstration site for academic and commercial use.

There are a wide range of capture technologies being developed in the UK, with some as new technologies, such as novel sorbents, but also the improvement of existing, mature technologies such as amine solvents. The key areas that capture technologies are being developed across all technologies are, lowing the energy cost of capture, increasing the percentage of capture, and ensuring that there are no major adverse emissions from the process, including from the chemicals used in the capture process.

Alongside the development of new technologies, the UK is working on improving existing technologies such as amines. This research is often fundamental or very early stage, such as the development of improved scrubbers, or can include the optimisation of systems through improved technology development. Advances in proven technologies can lead to an increase in the pace of roll out of technology.

New technologies often have research at multiple TRLs simultaneously. MOFs are an example of this where there is still early stage research being carried out, whilst there are also companies at TRL 5, preparing to develop small scale demonstrators

There is a relatively lower focus on CO_2 utilisation in UK technology development, possibly due to short term nature of storage in many of the CO_2 uses, such as fuels or chemicals where the CO_2 is likely to be rapidly reemitted and that this means that it will have little impact on reducing CO_2 emissions. The main forms of utilisation that are being developed for CO_2 are in aggregates and polymers, which are able to produce longer term storage for the CO_2 due to the durability off the material. This means that the utilisation is functioning as a storage medium as well.

Direct Air Capture is being developed in the UK and is still at an early stage of development through a recent funding competition which is supporting the early stage research into this technology. The first phase of projects has been released recently, and this is still a nascent industry. (Department for Business, E.& I.S, 2022b)

4.2.7 UK CCUS Policy and Regulation Landscape Discussion

The current policy scenario has laid out the basis to allow CCUS industry development. The Climate Change Act has set the framework and legally binding targets for emissions reduction. Storage of CO_2 Regulations created the basis to allow storage and the UK ETS established the framework for a market for emissions and emissions reductions with a price for tradable credits.

The challenges ahead are mainly related to the incorporation of CCUS into the CO_2 market mechanism and industrial deployment. As current deployment costs are still higher than carbon costs, long term commitments and transitionary arrangements backed by the government involving grants and revenue support play a crucial role on enabling and incentivising private investments. As technology evolves and show economic feasibility against CO_2 prices – expected to increase under the UKETS – the policies will need to transition to fully market-based mechanisms including robust frameworks to avoid carbon leakage and to support industry adoption of CCUS. Robust policy frameworks to support skills development and inform and engage the population will also be key to ensure public support, especially from the communities around the net zero hubs.

4.2.8 UK TEA & LCA Discussion

Harmonisation of LCA and TEA techniques to ensure comparable data between projects has been a key aspect of UK TEA and LCA publications. This includes NERC and EU funded projects, to develop robust methodologies. It will be key to ensure that these methodologies are consistent to ensure that projects are assessed equally in future. If there were a proliferation of standards due to these methodologies, it may create further confusion, although if government supported standards were set it could support alignment.

The government's development of business models is also an important step because the low current cost of CO_2 emission though trading schemes, compared to the cost of capture means that for the early stages of CCUS deployment, the government will likely be required to support the initial deployment schemes, as it has done through cluster sequencing. These publications, develop potential longer-term opportunities for companies to move beyond this and develop longer term strategies. The analysis by the industry bodies provides strong support economic support for the clusters but this is likely to be based on industry interests.

The environmental impact of CCUS is still not clearly established and there is significant potential research into this, particularly in the longer term, and the potential difficulties which could occur during its development. There is therefore potential for further research into this area and the costs and impacts which may need to be considered and/or addressed.

5 India Capability Results and Discussion

5.1 India CCUS Capability Results

This section presents the key findings related to the CCUS space in India.

5.1.1 India Universities Results

In India, many national, state and regional universities are actively engaged in studying various aspects of CCUS. During this study, 29 Indian universities working in CCUS research were identified and 7 of the Indian Institutes of Technology across India (IITs) are leading the CCUS research and development work.

Most of the universities are involved in research into carbon capture and utilisation, focussing on pathways for the energy and industrial sectors, whilst fewer universities are researching CO_2 storage and transport (Table 1.1). Many universities with expertise in marine chemicals, petroleum studies and ocean engineering are also exploring new CCUS technologies. Some smaller regional institutes like Marathwada Institute of Technology (MIT-e) and RKDF University are also researching carbon capture and utilisation technologies for a range of industrial sectors. IIT Bombay is the only university currently exploring CO_2 transport studies. Many of the universities are working directly with the industrial sectors to develop initial scoping and feasibility studies.

University Name	Location	C	U	T	S
Indian Institute of Technology, Bombay	Mumbai	x	x	x	x
Indian Institute of Technology Roorkee	Roorkee				x
CSIR-National Environmental Engineering Research Institute-NEERI	Nagpur	x			
CSIR-National Geophysical Research Institute (NGRI)	Hyderabad	x			
Indian Council for Research on International Economic Relations	New Delhi	x			
Ram Krishna Dharmarth Foundation University	Bhopal	x			
Jawaharlal Nehru Centre for Advanced Scientific Research	Bangalore	x	x		
Indian Institute of Science Education and Research	Kolkata, Pune	x			
CSIR-National Chemical Laboratory	Pune	x			
CSIR-Indian Institute of Petroleum	Dehradun	x			
Indian Institute of Science Bangalore	Bengaluru	x	x		
CSIR –Central salt & Marine Chemicals Research Institute	Bhavnagar	x	x		
Pondicherry University (Central University)	Pondicherry		x		
Pandit Deendayal Energy University	Gujarat	x	x		
Vaidya Institute of Chemical Technology	Mumbai	x			
CSIR-Indian Institute of Chemical Technology	Hyderabad	x			
Marathwada Institute of Technology (MIT-e)	Aurangabad	x	x		
Indian Institute of Technology, Gandhinagar	Gandhinagar	x			
National Institute of Technology	Tiruchirappalli	x	x		
Birla Institute of Technology and Science Pilani	Goa	x	x		

Indian Institute of Engineering Science and Technology	Shibpur	x			x
SSN College of Engineering	Chennai	x			
Indian Institute of Technology ISM	Dhanbad				x
Indian Institute of Technology, Madras	Chennai				x

This is a summary of Table 1.1 which can be found in the accompanying spreadsheet (Appendix 1, links to each university are also included).

For CO_2 utilisation, significant research has been carried out on CO_2 valorisation, methanol production, high-value organics production, and CO/CH_4 generation.

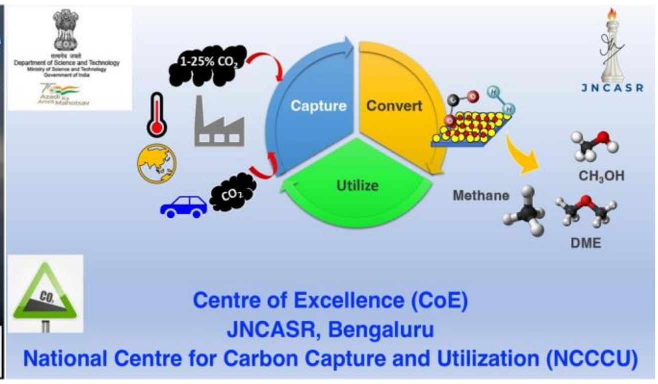
IIT Bombay and CSIR -National Geophysics Research Institute (NGRI) are working on various projects in geological CO2 storage with ONGC, Oil India Limited, etc and have been able to map various storage potential in saline aquifers, basalt formations, oil and gas reservoirs and unmineable coal seams Vishal et al., 2021). A majority of the universities in India are working on developing and optimizing capture technologies, like chemical absorption using hybrid solvents (Kumar and Shrivastava, 2019), membrane-based separation (Dey *et al.*, 2020), adsorption systems (Singh, Manpreet, et al, 2022) and oxyfuel combustion techniques (Majoumerd et al., 2017).

5.1.2 India R&D Institutes Results

The study identified 8 R&D institutions leading the CCUS research in India (Table 1.2).

Most of the R&D work on CCUS is led by IIT Bombay, National Chemical Laboratory, Central Salt & Marine Chemicals Research Institute (CSIR) and NGRI.

Department of Science & Technology (DST), India has also set up India's first two National Centres of Excellence (CoE) in the areas of Carbon Capture and Utilization, the National Centre of Excellence in carbon capture and utilization (NCoE-CCU) at Indian Institute of Technology (IIT) Bombay, Mumbai and the National Centre in Carbon Capture and Utilization (NCCCU) at Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR), Bengaluru. These centres work on science and technology programs for industry-oriented CCU innovation in India and also develop novel technologies for deployment. Enhanced hydrocarbon recovery is a priority area for the R&D institutes, in particular, the National Centre of Excellence which is looking to demonstrate effective CO_2 capture from flue gas produced from power and biogas plants. The NCCCU at JNCASR, Bengaluru, will be focusing on the development and demonstration of carbon capture and conversion by developing relevant materials. The centre will be focusing on the production of hydrocarbons like olefins, biofuels and other value-added chemicals. It will also promote CCU research, capacity building, economic and social impact.



The NGRI is also leading the CCS research with their expertise in site characterization, de-risking and uncertainty analysis and CO_2 sequestration projects across various geological structures in India.

The National Environmental Engineering Research Institute, (NEERI) at Nagpur is engaged in R&D projects focused on CCU in particular, covering both the capture and utilisation of CO_2.

R&D Centres	C	U	T	S
National Centre of Excellence – CCU, IIT Bombay	x	x		x
Indian Institute of technology-Delhi	x	x		x
National Centre in CCU- JNCASR, Bangalore	x	x		
Centre of Excellence in coal research at BHEL	x	x		
National Chemical Laboratory, CSIR	x	x		
National Environmental Engineering Research Institute, NEERI	x	x		
National Geophysical Research Institute NGRI				x
NETRA (NTPC Energy Technology Research Alliance)	x	x		

This is a summary of Table 1.2. which can be found in the accompanying spreadsheet. (Appendix 1, links to each university are also included).

5.1.3 India SMEs Results

There are currently few CCUS SMEs and start-ups in India (Table 1.3). Carbon Clean, a UK-Indian SME, has been a key player in the Indian CCUS space, partnering with many large enterprises in India using their amine-based solvent capture technology.

Another new start-up is Breathe Applied Sciences, which is a spin-out of a successful project at JNCASR, which converts CO_2 into methanol and other fuels. The current capacity of operations is 300kg per day. Breathe Applied Sciences recently won a national award from DST and the Technology Development Board (TDB) for its technology.

In newer technology development, Novonanmek Material Sciences Private Limited, which was set up in 2020, has developed its Direct Air Capture product under the brand Novoclime. The technology is currently in the piloting phase.

Company name	Main location(s)	Description of CCUS capability	C	U	T	S	TRL
Indian Farmers Fertiliser Co-Operative	Aonla, UP	IFFCO has been using amine solvents to capture CO_2 at its urea manufacturing plant in Aonla, UP. The system recovers CO_2 from the plant's natural gas-fired steam reformer flue gases, after which the gas is compressed and used for urea synthesis. The CO_2 absorber captures around 450 t/day CO_2 a day, and the facility has been in operation since 2006.	x				9
Indo Gulf Corporation Ltd	Jagdishpur, UP	Eco amine-based solvents using Fluor unit to capture CO_2 in urea manufacture capturing 150 t/day CO_2.	X				9
Indian Farmers Fertiliser Co-Operative	Phulpur, UP	IFFCO uses KM CDR Process® using amine solvents to capture CO_2 at its urea plant in Phulpur, UP. The absorber captures 450 t/day CO_2.	X				9
Carbon Clean	Mumbai, UK, US	Provides carbon dioxide (CO_2) separation technology for industrial and gas treating applications. The company's technology is used in power-plants, and steel, cement, fertilizer, chemical, and petrochemical industries for reducing CO_2 emissions.	X				9
Breathe Applied Sciences	Bangalore	Conversion of CO_2 to methanol and other chemicals.	X	x			6
Novonannek	Delhi	Direct Air Capture	X				4

This is a summary of Table 1.3. which can be found in the accompanying spreadsheet (Appendix 1).

5.1.4 India Large Companies Results

The majority of the early adoption of CCUS technology in India has come from the private players in the manufacturing industry (Table 1.4). In an IEA report on India's Energy Outlook for 2021, the manufacturing industry (cement, iron, steel) represents the 2nd largest sector emitting CO_2 in India, behind energy. The cement sector emits 211 $MtCO_2$ and the iron and steel industry emits over 300 $MtCO_2$. To reduce emissions, initial adoption of technology especially capture technologies, has been carried out by a small number of companies from sectors including cement, oil and gas and chemicals.

Company	Industry	Current Stage	Year Started	Technology	Capacity (t/y)
Tuticorin Alkali Chemicals	Chemicals	Full-scale deployment	2016	Amine based solvents	60,000
NALCO	Metals	Demonstration	2015	Microalgae carbon sequestration	
NTPC	Electricity	Demonstration	2021	Amine based solvents	7,300
BHEL	Electricity	Pilot	2011	Membrane technology for capture and methanol conversion	
Dalmia Cement	Cement	Pilot	2015	Amine based solvents	500,000
Tata Steel	Metals	Pilot	2021	Amine based solvents	1,825
ONGC	Oil & Gas	Feasibility Study	2019	Enhanced Oil Recovery	
IOCL	Oil & Gas	Feasibility Study	2019	CO_2 Capture	700,000
Reliance Industries	Oil & Gas	Initial Scoping	2020	Microalgae carbon sequestration, enhanced oil recovery	N/A
Hindalco	Metals	Initial Scoping	2019	Initial	N/A

This is a summary of Table 1.4. which can be found in the accompanying spreadsheet (Appendix 1).

5.1.5 India CCUS Projects Results

The majority of non-research based projects conducted have been set up by large private and public enterprises, with many of the projects incorporating start-ups like Carbon Clean (Table 1.5).

NTPC, along with Carbon Clean and IIT-Bombay has set up a demonstration project at the NTPC Vindhyachal coal-fired plant where captured CO_2 will be converted into various products, including soda ash, methanol and urea.

Project name	Main location(s)	Leading participants	Description of project	FID and Capture Target
Pilot- Carbon Sequestration	Tamil Nadu	NALCO	CCS pilot in its Captive Power Plant at Angul using microalgae to capture CO_2	Completed (2014) 36-54 t/acre/year
Carbon Capture for Enhanced Oil Recovery	Koyali, Gujarat	ONGC IOCL Dastur	Techno-economic feasibility of the Indian Oil Corporation Ltd's (IOC) Carbon Capture and Utilisation Project at the 13.7 Mt/year Koyali refinery in Gujarat.	Completed (2022) 0.7 t/year
Amine-based capture plant for the Cement Industry	Ariyalur, Tamil Nadu	Dalmia Cement	ABPS solvent-based capture solution developed along with Carbon Clean for Carbon Capture plant	Ongoing (2019)
Amine-based capture pilot for the Steel Industry	Jamshedpur, Jharkhand	Tata Steel	Tata Steel commissioned a carbon capture plant at its Jamshedpur Works, to adopt amine based carbon capture technology with Carbon Clean that extracts CO_2 directly from the Blast Furnace gas.	Completed (2021) 5 t/day
NETRA CCU Pilot Project	Noida	Green Power International, Carbon Clean, IIT Bombay	Pilot project to capture CO_2 to convert to methanol, urea,	Ongoing (2022) 20 t/day

This is a summary of Table 1.5. which can be found in the accompanying spreadsheet (Appendix 1).

5.1.6 India CCUS Technologies Results

CCUS technology in India is at a nascent stage considering investment and the requirement to upscale novel technologies for capture, utilisation and storage. A global technological readiness level available for monitoring the deployment capabilities (Bui et al. 2018) and a preliminary analysis of the TRLs technologies in India was conducted recently (Table 1.6).

Technology Type	Technology name	Leading participants	TRL
Carbon Capture	Fluor Eco amine FG technology	IFFCO, Mitsubishi	9
Carbon Capture	Amine solvents and Enzymes, Membranes	ISER Kolkata, CSIR-CSMCRI, CSIR-NEERI, CSIR-NCL, CSIRIICT,IOCL	5
Carbon Capture	Amine-Promoted Buffer Salts (APBS) based Solvents	Carbon Clean, Tata Steel, TAKL, Dalmia Cement, NTPC	9
Carbon Capture	Adsorption	NTPC	8
Carbon Capture	IGCC	IOCL	8
Carbon Capture	Oxy combustion	BHEL	5
Carbon Capture	Ionic Liquids	IIT Delhi	4
Carbon Capture	Chemical Looping	IOCL	3
Carbon Capture	Calcite looping	NTPC	3
Carbon Capture	Direct Air Capture	Novoclime	1
Carbon Capture	Polymer Membranes	Indus university	3
Carbon Utilisation	Enhanced oil recovery	IOCL, OIL, ONGC,IIT Bombay,Dastur International Inc.,Dastur Energy, Toyo Engineering India Private Limited.	5
Carbon Utilisation	Enhanced coalbed methane recovery	IIT Bombay,ONGC, Essar O&G EPL	3
Carbon Utilisation	Algae fixation	NALCO, Reliance	6
Carbon Utilisation	Chemicals conversion to methanol	JNCASR Bengaluru, IIT Delhi, CSIR-NCL, Breathe Science, L&T, NTPC	8
Carbon Utilisation	Chemical conversion to DME	CSIR, IIT Delhi	6
Storage	Depleted oil and gas reservoir	IIT Bombay, PDEU, IIT Madras, NGRI, ONGC, OIL,RGIPT, IIT Guwahati	4

Storage	Saline Aquifer	NGRI, IIT Madras, IIT Bombay	3
Storage	Mineral Storage	Delhi University, NGRI, IIT Bombay	4
Storage	Coal and Shale	IIT Bombay, IIT ISM Dhanbad, IIEST Shibpur	4

This is a summary of Table 1.6 which can be found in the accompanying spreadsheet (Appendix 1).

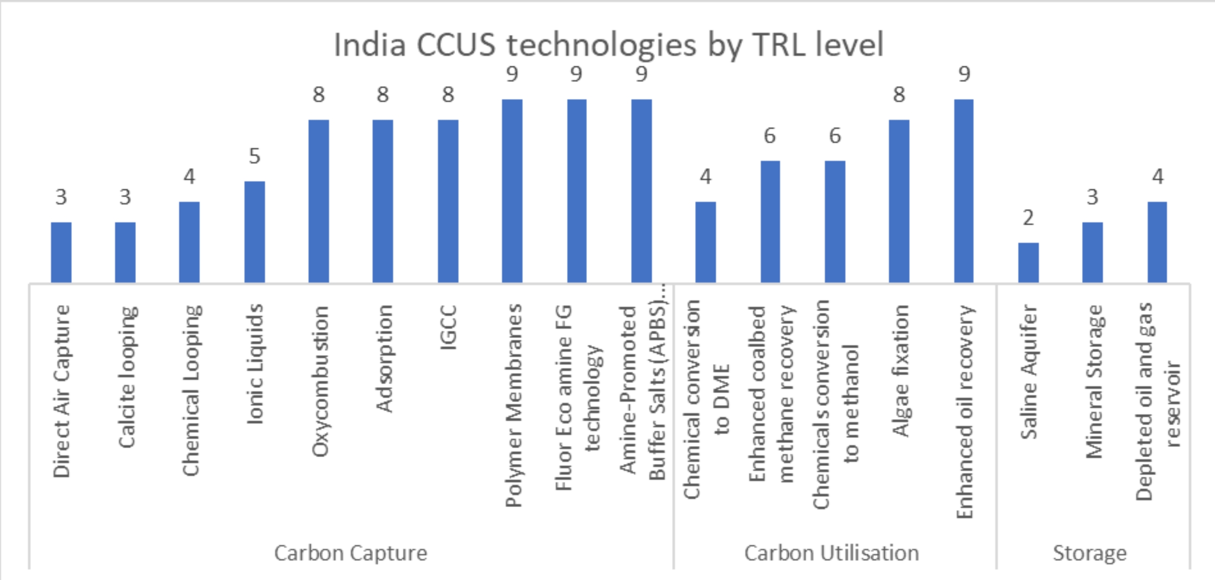


Figure 6: India CCUS technologies by TRL level.

Figure 6 above highlights the various technologies from TRL3 to TRL 9 being developed in the Indian landscape.

5.1.6.1 Capture

The technology in carbon capture is mostly at an early stage of development, mostly below TRL 4. The Post Combustion technologies in adsorption and amines are at a higher TRL due to their successful deployments both in India and internationally. Amine based capture plants have been operational at three urea manufacturing plants Aonla (450 t/day), Phulpur (450 t/day) and Jagdishpur(150 t/day) (Gupta and Paul, 2019). The amine-based technology (Fluor Ecoamine FG) has also been operational at a large-scale fertilizer plant capturing 150 t/day from a flue gas ammonia reformer since 1988. Other technologies like ionic liquids, have demonstrated high selectivity, good recycling ability and high yield of products.

Innovation around calcite looping and fluidized bed combustion (FBC) are being assessed (simulation) for techno-economic feasibility in Sipat, Chhattisgarh. The initial results have revealed cost benefits and a low energy penalty for the proposed retrofitting of the plant (Iyer, Rao and Banerjee, 2020). An integrated gasification combined cycle with chemical looping in Indian Coal has identified minimum efficiency reduction. (Shijaz et al., 2017). Early studies on carbon capture, using biological methods, such as seagrass and algae production in Palk Bay area, Odisha, are being carried out (Behera, Aly and Paramasivan, 2020; Ganguly *et al.*, 2018).

5.1.6.2 Utilisation

CO_2 utilization technology is considered a promising area with the TRL 9 project at Tuticorin Alkali Chemicals with Carbon Clean where captured CO_2 is converted into soda ash. Soda ash (Sodium Carbonate) has various uses, especially in the laundry detergent industry and is typically produced using the Solvay method which is an energy-intensive process and includes the coking of coal. This makes CO_2 conversion to soda ash a more viable, cleaner solution.

CO_2-EOR and CO_2-ECBM recovery technologies are also undergoing technical feasibility studies and remain promising areas of potential research. Long-term feasibility assessment for CO_2-ECBM recovery has been conducted at two coal fields in Dankuni, Raniganj in East India (Vishal V, Mahanta B et. Al) and there is ongoing development of methanol plants in Dankuni, East India by Coal India Ltd (TNN, 2020). An indigenous technology is being developed by BHEL to convert high ash Indian coal to methanol and has established its first pilot plant in Hyderabad (Department Of Science & Technology, 2021) this conversion of high-ash Indian coal to methanol through the gasification route is the first-of-its-kind technology demonstration in India.

Microalgae based utilization technologies are studied for the feasibility of bioconversion of CO_2 into biofuels. Currently, pilot scale facilities are being set up at Hazira, India for algae-based CO_2 fixation (Yadav et al., 2016).

5.1.6.3 Transport and Storage

Storage technologies are at lower TRL and are currently being explored for deployment. Considerable work has been carried out in the area of mineral sequestration in Eastern Deccan Volcanic Province. Long-term storage behaviour of mineral formation mechanisms and thermodynamics are being studied. (Kumar et al., 2017; Kumar and Shrivastava, 2019). Currently, various monitoring technologies are being developed for pressure monitoring, modelling tracers, seismic imaging and annulus monitoring. Technologies for vertical leakage like microseismic imaging, tiltmeters and satellite imagery are developed. Advance storage technologies in saline aquifers and ocean storage are at a very early stage in India.

There has been limited research into CO_2 transport, with some high TRL technologies based on the history of natural gas transport and storage infrastructure across national pipelines, such as the Urja Ganga pipeline of GAIL India (Press Information Bureau, 2019). There is a limited data on the identification of the actual TRL.

Overall, CCUS technology in India has begun to be deployed, subject to limitations due to operational cost considerations and scalability. The UK's approach to the CCUS technology is important in cost reduction and scalability in Indian context.

5.1.7 India CCUS Policy and Regulation Landscape Results

While no India-specific CCUS policy has been released, various action plans and government initiatives highlight the direction of CCUS development in India in the coming years (Figure 7).

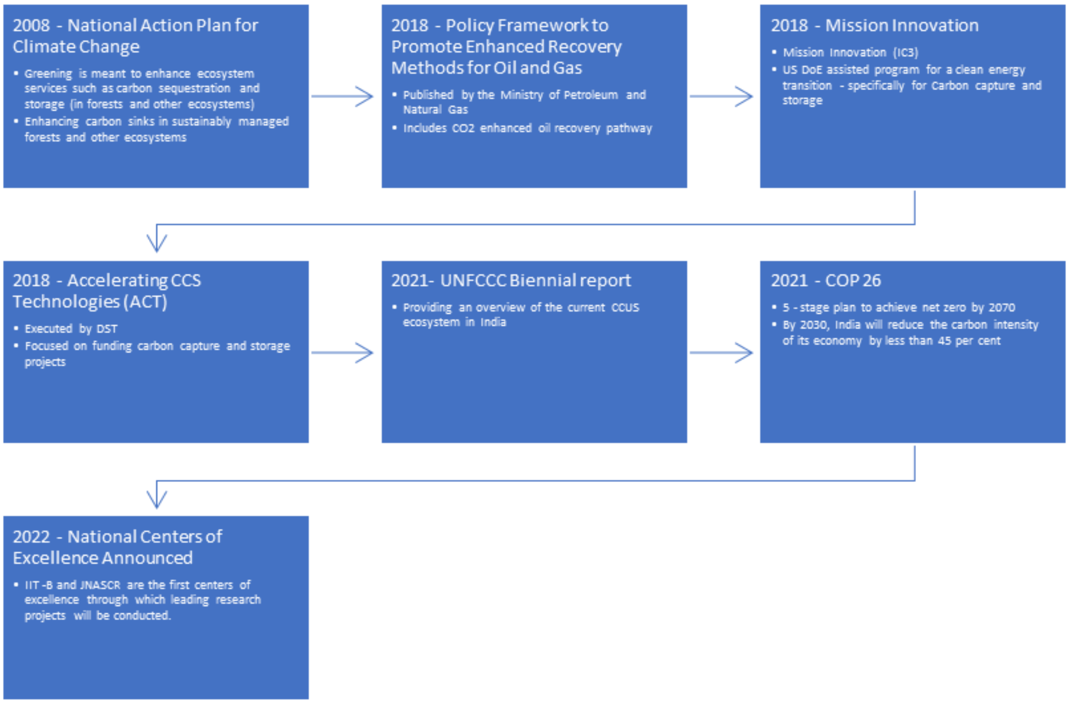


Figure 7: Timeline of Indian CCUS relevant policy and regulation

The only policy that explicitly mentions CCUS is from the Ministry of Petroleum and Natural Gas which mandates all oil fields in India be assessed for potential Enhanced Recovery solutions, with one of the solutions being CO_2 injection for EOR and EGR.

The Indian government has also mentioned CCUS at international climate change-focused convenings, discussing India's overall decarbonization goals, as well as describing the current activities in CCUS in India.

The announcement of India's first National CCU Centres of Excellence (See section 5.1.2) will support the development of new technologies and the ultimate scale up for widespread deployment.

5.1.8 India TEA & LCA Results

Over the last 10 years, several capacity assessments and sector overview studies have been conducted by research institutes and think tanks, based in India (Table 1.8). This includes CEEW's study on Carbon Capture, Utilisation, and Storage in India (Malyan, Chaturvedi 2021). This has followed several high-level scoping studies conducted in 2013 by TERI and TIFAC in 2018. The studies have highlighted increased deployment, especially in capture and utilisation technologies, with key industrial projects being conducted in carbon-intensive industries.

The major companies mentioned are the coal, oil and thermal power industries. The main research bodies in India that have conducted TEA and LCA include IIT-Bombay and IIM-Ahmedabad universities and the Centre of Excellence in Coal Research at BHEL.

Title of leading TEA and LCA CCUS publications	Lead author	Year
Cost implications of Carbon Capture and Storage for the Coal Power Plants in India	Anand B. Rao, Piyush Kumar	2014
Techno-economic analysis of Carbon Mitigation Options for Existing Coal-fired Power Plants in India	Udayan Singh, Anand B Rao	2016
An improved tri-reforming based methanol production process for enhanced CO2 valorisation	Abhishek Dwivedi, Ravindra Gudi, Pratim Biswas	2017
Economic Implications of CO2 Capture from the Existing as well as proposed coal-fired power plants in India under various policy scenarios	Udayan Singh, Anand B Rao, Munish K. Chandel	2017
Relevance of Carbon Capture & Sequestration in India's Energy Mix to achieve the reduction in emission intensity by 2030 as per INDCs	A.R. Akash, Anand B. Rao, Munish K. Chandel	2017
Carbon capture and sequestration potential in India: A comprehensive review	Abhishek Gupta	2018
Oxy-fuel combustion-based enhancement of the tri-reforming coupled methanol production process for CO2 valorisation	Abhishek Dwivedi, Ravindra Gudi, Pratim Biswas	2018
Evaluation of Techno-Economic Viability of Carbon Capture Utilisation and Storage (CCU&S) with Carbon Credits for Steel Plants	Arunava Maity	2021
Techno-economic analysis of a 660 MWe supercritical coal power plant in India retrofitted with calcium looping (CaL) based CO2 capture system	Srinath Iyer	2021

This is a summary of Table 1.8 which can be found in the accompanying spreadsheet (Appendix 1).

5.1.9 India Stakeholders Map

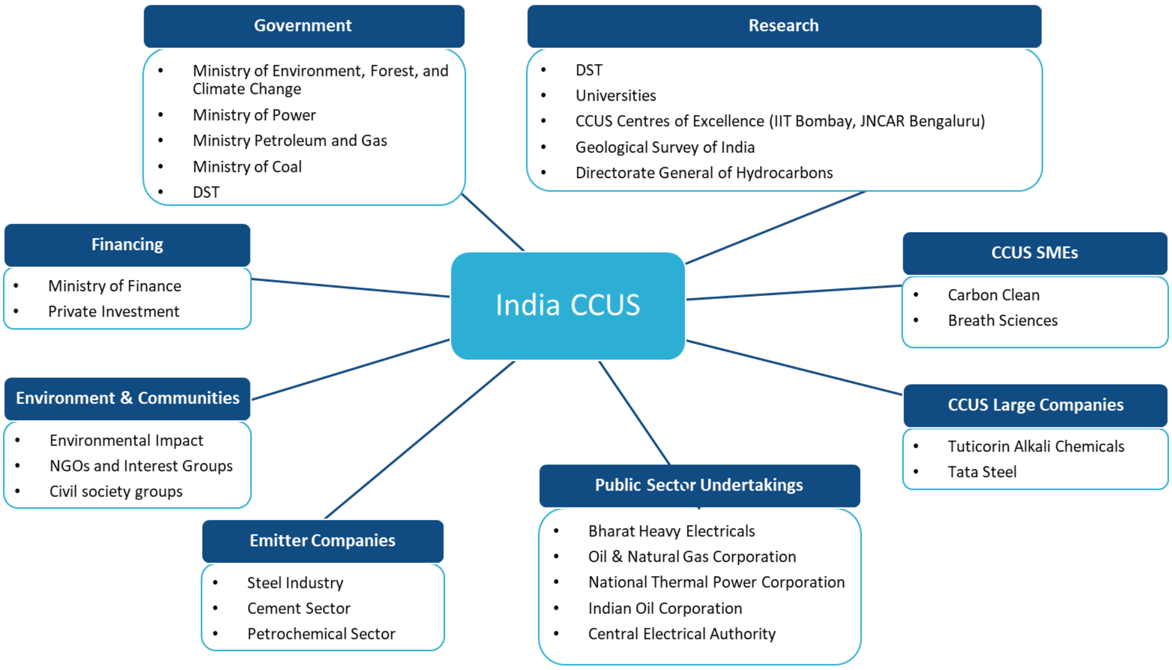


Figure 8: India CCUS stake holders map. Please refer to the accompanying spreadsheet (Appendix 1) for more details.

With the CCUS sector in India at a nascent stage, different ministries, PSUs and research institutions are involved in several aspects of CCUS, independent of each other (Figure 8). This may be caused by no CCUS overall policy being issued by the government at this stage. While the ministries (including MoPNG, MoC, MoP, MoEFCC) have been more involved with planning for the next phase of CCUS, PSUs like BHEL, ONGC, NTPC, IOCL have been involved in project implementation through pilots and demonstrations. DST has been the most active of the government bodies, pushing for advancements in research by running the Mission Innovation and ACT programmes, while influencing policy especially on the future of carbon capture and utilisation. Think tanks have mainly been involved in scoping studies, TEA/LCA, and overall reporting of current activities in CCUS.

CCUS is gaining traction in India, as an effective strategy to contribute to the nation's net-zero goals. Although CCUS has been explored in India since 2007 and some early adoption of the technology in manufacture industries, there has been accelerated work at the national level more recently.

5.2 India CCUS capability discussion and insights

5.2.1 India Universities Discussion

Many national universities and research centres are engaged in the CCUS research on various capabilities and are supported by DST, India. The research capability in India is demonstrated in CCUS, with a more minor interest in CO_2transport. These organisations are consistently working on developing novel capture technologies, utilization pathways and storage potential across the country. India has also established a strong network for collaboration and partnerships at global level.

Universities have developed facilities and centres of excellence to focus on improving the technological readiness for existing solutions and are developing new and novel technologies. The identification of 13 clusters for storage research will provide wider opportunities for scientific advancements and supporting infrastructure.

Similar to the UK research infrastructure support, Indian academia has also supported the demonstration and trial of new technologies leading to spin outs from the universities like Breathe Sciences from JNCASR.

The research priorities in CCUS remain strong at capture, utilization and storage. Primarily focused on EOR and ECBM utilization-storage, various utilization pathways to higher value chemicals, monitoring of geological storage, and developing novel solutions in capture.

5.2.2 India R&D Institutes Discussion

Indian R&D is critical in leading CCUS research, playing a major role in a range of areas including subject matter experts and technical expertise, monitoring and evaluation, and influencing policy through advocacy. They are promoting advanced research, capacity building, consultancy, and the social impact of CCUS. These organisations are also instrumental in leveraging industry to improve the technology readiness, feasibility, and initiate pilots. The two new R&D institutes in Mumbai and Bengaluru will be leading the development from strategic level and potentially provide opportunities for collaboration with the larger research network. They will be also engaged in driving the research in priority areas like novel methodology development, various utilization pathways, and monitoring storage. NGRI will be particularly considered for any carbon storage-based research and opportunities for collaboration/joint programs.

5.2.3 India SMEs Discussion

The number of CCUS start-ups in India is expected to increase, following the trend that start-ups are set up as offshoots of successful research projects at key universities. Carbon Clean, headquartered in London with offices in India was founded based on research at IIT Kharagpur and Breathe Applied Sciences at JNCASR. This could be true especially after the completion of the Mission Innovation and ACT projects.

5.2.4 India Large Companies Discussion

Most of the large companies in India that have been looking to incorporate CCUS technology as part of their operations have only started showcasing their recent interest in the last 3 years. Only Dalmia Cement, Tuticorin Alkali Chemicals and NALCO have been active in the CCUS sector in the past 10 years. This work is being accelerated because of net-zero commitments within the large enterprises. While India looks to achieve net-zero by 2070, the majority of the companies listed above have set ambitious targets to achieve net zero between 2030 and 2050, signalling a push for adoption of CCUS technology in the coming years.

5.2.5 India Projects Discussion

Major projects are demonstrated at industrial level, led by the large PSUs, private companies and academia. Large enterprises like NTPC (Energy), BHEL (Energy), IOCL (Oil and Gas), Dalmia (Cement), Tata (Steel) and NALCO (Aluminium) are operating large scale projects at various stages although many of them are at pilot, feasibility or scoping phases. NTPC and NALCO are engaged in demonstration projects in capture and algae-based sequestration respectively.

New projects in amine-based capture technology have successfully been deployed in the last 5 years as a result of Carbon Clean's successful work with Dalmia Cement and Tuticorin Alkali Chemicals. This suggests that once Indian CCUS technologies move beyond TRL 4, more companies in oil & gas, metals and cement industries could be open to conducting pilots and demonstration projects in the future.

5.2.6 India Technologies Discussion

CCUS technologies in India are at an early stage, working on improving the technology readiness and feasibility for deployments. The success of Carbon Clean's amine based solvent capture technology, which started with Tuticorin Alkali Chemical's capture project has seen several large companies in India engage with Carbon Clean for pilots and demonstration activities. Large enterprises are actively engaged in implementing CCUS in their operations with industries like steel, cement, oil, gas, petrochemicals leveraging carbon capture and utilisation technology. Successful demonstration projects in CO_2 utilisation, especially on conversion technology, have been encouraging, leading to future opportunities for large scale deployments. EOR and ECBM are particularly gaining momentum due to their scale and feasibility. Several utilisation pathways have been identified in production of various value-added chemicals. The potential storage capacities of a range of geological formations in India are being studied and assessed , highlighting the storage potential. Storage technologies are still in development; verification and accounting are being researched and in particular, their efficacy toward vertical leakage, injection well problems and wellbore leakage.

5.2.7 India Policy And Regulation Landscape Discussion

Many of the announcements, policies and support from the government has focused on wider environmental goals (which CCUS may fall under), which includes the funding of capture technologies and a call to assess natural storage capabilities for India. To further align the CCUS ecosystem bringing together various stakeholders including SMEs, research organisations, and large enterprises under one plan, a CCUS specific policy/action plan released by the government would be beneficial. This policy would chart out a clear timeline, highlighting goals for research, for deployment, and alignment of key CCUS stakeholders.

5.2.8 India TEA & LCA Discussion

Given India's high coal dependence, studies have been conducted to calculate the cost implications of installing CCUS at coal power stations. (A. Rao et. Al, 2014). These studies showed that retrofitting capture technology could increase the cost of electricity by 18% and would require new coal plants to be designed to incorporate the technology. A further economic feasibility study in coal (U. Singh et. Al, 2017) shows that incorporation of CCUS technology especially in capture has been made more feasible for the coal industry with advances in amine-based solvent technology but can only be economically feasible at a large scale in scenarios where there are high prices ,prices, which is expected to be become more likely in future.

A techno-economic feasibility study of utilisation pathways may be appealing as economies of scale are achieved. For instance, the cost of methanol production through CCU could be brought below the current market price of \$200/t CO_2 by 2035. (IRENA, 2021)

With India's push to reduce its carbon intensity, as highlighted in its INDCs and more recently at COP 21 where it pledged to reduce its carbon intensity by 45% by 2030, studies have been conducted to highlight the relevance of CCUS in India's energy mix. In a study conducted in 2016 (A. R. Akash et. Al, 2017), while India has taken a stance to reducing carbon intensity via increased capacity of renewable energy, India is expected to achieve its goals without significant CCUS. However, CCUS in India has the potential to curtail large amounts of GHG emissions from the source and if India's targets were made more stringent by or before 2030, CCUS would be the best alternative method of carbon intensity reduction.

Overall, the coal industry has been well analysed especially because of the high level of carbon intensity in the industry. This level of analysis can be conducted across the other carbon intensive industries like oil & gas, cement, metal. This would provide strong support to the active industries looking to incorporate CCUS technology as part of their operations, identifying viable pathway for large scale CCUS deployment in India.

6 UK Research Landscape Results and Discussion

6.1 UK Research Landscape Results

6.1.1 UK CCUS Research Projects Results

There has been a wide range of research into CCUS in the UK which is ongoing or which has been recently completed (Table 2.1). It is predominately focused on capture research, as shown in Figure 9 below, with other interest in storage and significantly less focus on utilisation and transport. The research has been funded through a range of networks, both domestic such as the UKCCSRC and the Scottish CCS Centre, but also international programmes such as ACT, and Align CCUS.

The current core UK funding round of £6.1m from 2017-22, funded by EPSRC, and coordinated by UKCCSRC, covers 15 projects across three core themes, Capture, Storage, and Systems and Policy. The capture projects focus on the development of new capture technologies and the optimisation of existing processes, storage projects focus on topics covering the behaviour of the plume within storage reservoirs and the monitoring of storage sites, and Systems and Policy projects covers the full integration of CCUS into wider energy networks and energy systems modelling. The Systems work also covers social aspects of CCUS such as public acceptance and license, including BECCS. The interaction of the different research areas, and the interlocking nature of the research is shown in Figure 10 below. (UKCCSRC, 2022)

The UKCCSRC also offers flexible funding to address key research gaps which it has identified though specific meetings through the duration of this funding cycle, covering 24 smaller research grants, totalling an additional £1.5m in funding between 2017-22.

The key subject areas within this, as covered by current flexible funding grants include monitoring and storage through non-traditional technologies (utilisation of quantum sensors and autonomous drones), MOF (metal organic frameworks) based capture technologies, improvements to amine life-cycle and efficiency, BECCS practical application and social acceptance, and early stage Direct Air Capture technologies.

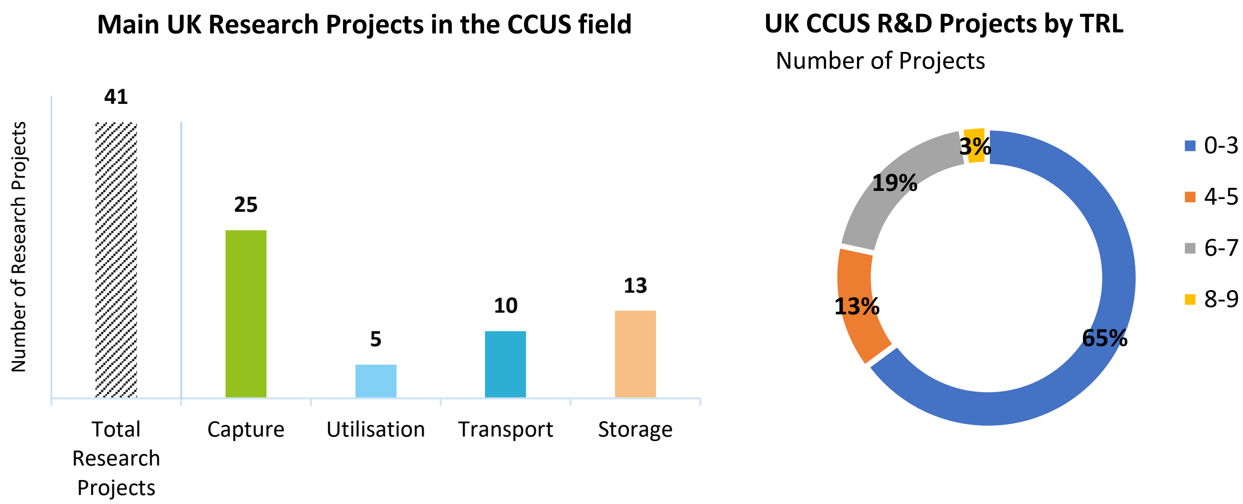


Figure 9: Main UK CCUS projects identified in the research by focus area and TRL level.

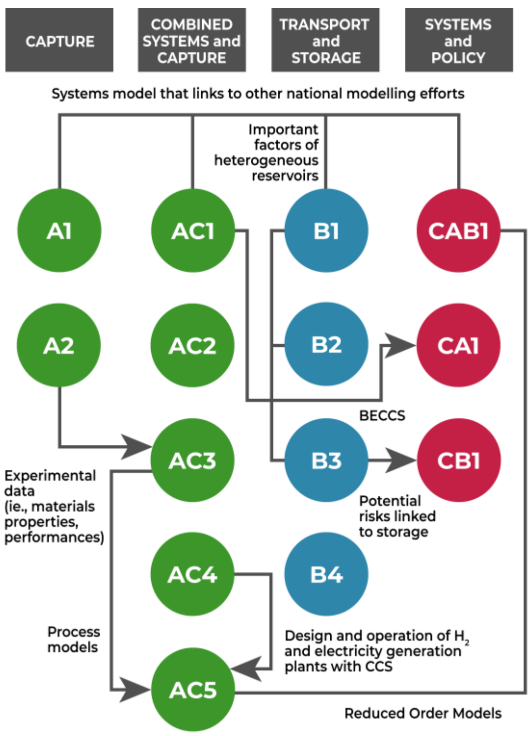


Figure 10: Image of UKCCSRC core research projects 2017-22, showing the links between research projects. Source: UKCC RC official website (https://ukccsrc.ac.uk/research/core-research-projects/)

There has also been funding available through EU programmes, such as ACT, which has included storage research at the University of Edinburgh and Herriot Watt University. The National Oceanography Centre in Southampton, is also carrying out research into CCUS, including offshore storage monitoring through the STEMM-CCS and CHIMNEY projects, which included leak detection and autonomous drone monitoring technologies.

Alongside technical research, there is also research into the economic, life-cycle, social and environmental impacts of CCUS. This has included research by the Tyndall centre in Manchester, through UKCCSRC, which has focused on the actions required for CCUS to gain the social license to operate, and how this is affected by the presence of CCUS projects. The social license to operate has also been researched by the government, through an examination of public attitudes towards CCUS.(UKCCSRC, no date b; Gough and Mander, 2019)(Macgillivray and Livesey, 2021)

TEA and LCA research in the UK has often focused on developing consistent methodologies, to ensure that assessments of potential projects are consistent. This research has been included in the core research projects, both with in the UK and international projects. This work has been carried out by the University of Sheffield, linking their knowledge and experience of the technical aspects of the system to increase understanding of the economic aspects.(Zimmermann *et al.*, 2020)

The economic aspect of CCUS, examined through TEA and LCA analysis covers the long-term costs of installation and operation of a CCUS plant, based on both BAT at the current and future technology curves. LCA analysis also covers the environment impacts of these technologies, including the potential for pollution which can arise from waste products of capture processes.

Project name	Technology name	Leading participants	Year
Capture: A2b, Pilot Testing #2	Capture	Cranfield University	2019-22
Combined systems and capture: AC3, Detailed Models	Capture	University of Cambridge	2019-22
Capture: AC5, Reduced Order Models (ROMs)	Capture	University of Sheffield	2019-22
Launch	Capture	EU+USA programme, Edinburgh+Sheffield	2019-22
Advancements in mixed amine atmospheric kinetic models	Capture	University of Sheffield	2021
Autarkic embedded Direct Air Capture for breakthrough cost reductions	Capture	University of Nottingham	2021
Development of an energy-efficient and cost-effective catalytic regeneration system in the post-combustion CO_2 capture process	Capture	University of Hull	2021
Fugitive amine emission scrubbing using electrostatic precipitation	Capture	Cranfield University	2021
PCC-CARER: Post-Combustion Capture – Cost And Residual Emission Reduction	Capture	University of Sheffield	2021
Pilot Scale Carbon Capture using Solid Sorbents PICASSO	Capture	University of Nottingham	2021

Scale up of F4_MIL-140(Ce) for next generation carbon capture (F4-Next-CC)	Capture	Swansea University	2021
Co-Cap: Collaboration on commercial capture	Capture	Prof Jon Gibbins, University of Sheffield	2020
CO_2-FROST: CO_2 frost formation during cryogenic carbon capture with tomography analysis	Capture	Dr Carolina Font-Palma, University of Chester	2020
Evaluation of different CCUS systems based on the MCFC technology for decarbonising the power generation sector	Capture	Prof Lin Ma, University of Sheffield	2020
Biomass combustion ash in carbon capture	Capture	Dr Salman Masoudi Soltani, Brunel University London	2020
Accelerating Basic Solid Adsorbent Looping Technology	Capture	Professor Snape, University of Nottingham	2021
Align CCUS	Capture, Storage, Transport, Utilisation	EU wide programme, including Heriot Watt, BGS, ICL, PACT, University of Edinburgh	2017-2021
Combined systems & capture: AC1, BECCS	Capture	University of Sheffield	2019-22
Combined systems & capture: AC2, Advanced high-efficient cycles using gas turbines with S-CO_2 or direct oxy-fired CCGT-CCS	Capture	University of Sheffield Cardiff	2019-22
Capture: AC4, Integration options for hydrogen and clean power synergies null	Capture	University of Edinburgh	2019-22
Techno-economics of Biomass Combustion Products in the Synthesis of Effective Low-cost Adsorbents for Carbon Capture	Capture	Brunel University London	2021
Cucurbit[5]uril-incorporated photocatalytic membrane for carbon capture and utilisation	Capture, Utilisation	Prof Junwang Tang, University College London	2020

Capture: A1, Materials Development	Capture	Imperial College London	2019-22
Capture: A2a, Pilot Testing #1	Capture	University of Nottingham	2019-22
Systems & Policy: CAB1 – Cross-cutting Value of CCS	Policy	Imperial College London, UCL	2019-22
Systems & Policy: CA1 – BECCS within the energy system	Policy	Imperial College London	2019-22
Systems & Policy: CB1 – Social license to operate	Social Impact	Tyndall Centre at University of Manchester	2019-22
SECURe	Storage	BGS, Heriot Watt, Edinburgh, Nottingham	2019-2021
Feasibility study into Quantum Technology based Gravity Sensing for CCS	Storage	University of Birmingham	2021
Sensor Enabled Seabed Landing AUV nodes for improved offshore Carbon Capture and Storage (CCS) monitoring	Storage	National Oceanography Centre Southampton	2021
SCARP North Sea: Storage Challenge and Reserve Provision, a fundamental gigatonne CO_2 challenge for European net zero	Storage	Prof Stuart Haszeldine, University of Edinburgh	2020
Storage & Transport : B1, Pressure Propagation & Control	Storage	University of Edinburgh, Imperial college London, University of Cambridge, BGS	2019-22
Storage & Transport: B2, CO_2 Migration & Storage	Storage	University of Edinburgh, Imperial college London, University of Cambridge, BGS	2019-22
Storage & Transport: B3, CO_2 Modelling Assessment	Storage and Transport	University of Edinburgh, Imperial college London, University of Cambridge, BGS	2019-22

Storage & Transport: B4, Scoping/Development of a Proposed CO_2 Geolab	Storage	University of Edinburgh, Imperial college London, University of Cambridge, BGS	2019-22
Forge	Transport	TWI	2020
PilotSTRATEGY	Storage	EU programme across 5 countries	2020
Advanced Multitemporal Modelling and Optimisation of CO_2 Transport and Storage Networks	Storage and Transport	Professor Korre, Imperial College London	2021
Recovering liquefaction cost of captured carbon dioxide by cold energy utilisation and electric power generation	Transport	Dr Kumar Patchigolla, Cranfield University	2020
Monitoring of CO_2 flow under CCS conditions through multi-modal sensing and machine learning	Transport	Prof Yong Yan, University of Kent	2020
CoCaCO_2La	Utilisation	Damien Kirkpatrick, TWI	2021

This is a summary of Table 2.1 which can be found in the accompanying spreadsheet (Appendix 1, links to each university are included).

6.1.2 UK CCUS Research Networks Results

The UKCCSRC and SCCS Centre are the leading the co-ordination of UK CCUS research through government funded programmes (Table 2.2). (SCCS, no date; UKCCSRC, no date a)These organisations assist in the distribution of government funding and have been key in deciding the core research areas. The UKCCSRC also holds annual workshops to discuss the key areas where there are outstanding gaps in research and have been able to provide some flexible funding to address these concerns.

There are also international research networks which have worked to develop research projects which includes ACT.

The professional network in the UK linking CCUS is the Carbon Capture and Storage Association, CCSA, which acts as a group linking a wide range of organisations involved in CCUS in the UK, primarily industry. It also publishes briefing documents and consultation responses to policy and research.(CCSA, website accessed April 2022)

Previous UK research networks include CO_2Chem, focused on CO_2 utilisation and valorisation which was led by the University of Sheffield. The programme, funded by EPSRC, focused on the use of CO_2 as a feedstock for the production of value added product and chemical synthesis.(CO2CO2Chem, website accessed April 2022)

Research Network Name	Description of research activity
UK CCS RC	UK CCS research network, funded by EPSRC, bringing together a wide range of academic institutions to coordinate research for all aspects of CCUS. Promotes UK CCUS research, including holding MoU's with CCUS organisations in 6 other countries (Australia, Canada, China, Netherlands, South Korea, USA.
Scottish CCS Centre	SCCS is the largest CCS research group in the UK, providing a single point of coordination for CCS research, from capture engineering and geoscience to social perceptions and environmental impact through to law and petroleum economics.
Accelerating CCS Technologies (ACT)	ACT is a global CCS research funding group, originally designed to run from 2016-21, but has since been extended under ACT3 – including funding from both UK and India, among others. They have funded a wide range of projects. 40 kt/year The Research Council of Norway (RCN) is coordinating ACT.
UKERC Energy Data Centre: Data Catalogue	Database containing existing data stores
CCSA	UK Trade Association for the CCUS industry, covering more than 80 companies. This includes Law Firms, SMEs, O&G majors, from all parts of the value chain
CO_2Chem	A previous EPSRC Grand Challenge Network that was focused on delivering research into the utilisation of CO_2 as a chemical feedstock.

This is a summary of Table 2.2 which can be found in the accompanying spreadsheet (Appendix 1, links to each university are included.

6.2 UK Research Landscape Discussion and Insights

6.2.1 UK CCUS Research Projects Discussion

The UK has a complex research landscape for CCUS.UK research covers all key aspects of CCUS, although there is a particular emphasis on capture in UK research projects with 90% of the universities in this report covering capture though their research. Utilisation (55%) and storage (45%) are also covered by significant proportions of universities, but only 30% include transport as an area of research.

The key focuses have been to deliver improved capture technologies, establish standards for TEA and LCA, improve the understanding of fundamental parts of CO_2 storage, particularly monitoring and the available capacity, and develop models for the integration of CCUS into the wider landscape.

Transport has not been a key focus, likely due to CO_2 transport being a mature technology which is used at a commercial scale globally, such as the significant existing pipelines which are present in the USA, with 6500km of CO_2 pipelines, and the aim of many projects to adapt existing natural gas pipelines to transport CO_2.

Storage research is focused on geological storage, including the long term monitoring of storage sites to ensure that carbon remains stored and the behaviour of CO_2 plumes in storage formations. This area of research is also linked to the environmental and social aspects of CO_2 storage. The environmental impacts of storage, and of any leaks must be monitored for marine life, and for CO_2 storage to gain social licence, it must show that the storage is effective in the long term and that there are no leakages from storage.

Some storage and utilisation research is linked where CO_2 can be stored in a usable product such as aggregates (Carbon8, OCO, Sphera) or fertiliser (CCM), adding value to the waste CO_2, which would otherwise be a cost to store geologically. There is also a link between universities studying transport and geological storage, because there are large cross over areas and interlinkages. This is important because the UK has focused more on storage as the long-term sink for CO_2, rather than on utilisation.

Utilisation research covers a wide range of potential uses for CO_2, including fertiliser, polymers, chemicals, and aggregates, all of which add additional value, compared to the cost of storing CO_2 geologically (IEA, 2019b). Utilisation, however, often does not lead to long term storage of CO_2, as the CO_2 is re-releasedCO_2 during the use phase of the product lifecycle. An example of this is fertiliser or a chemical which is consumed in the process. Utilisation of CO_2 is also likely to only play a small part in the overall CO_2 storage, with most predictions assuming that it may only account for c.10% of CO_2 in 2050 (IEA, 2019a, 2019b). This short storage duration means that it has been relatively less favoured in government policy and in previous research funding.

Capture research is present at nearly all institutions in the landscape, including both point source and direct air capture methods, using a diverse range of technologies, and a broad range of TRLs. Key aspects of this research are to push established amine capture technologies to 95%+ capture efficiency, and to reduce the presence of pollutant side products in the final emissions, such as nitrosamines. These are being researched to take advantage of the existing engineering developments for amine based capture systems, as new solvents are often drop in replacements (UKCCSRC, 2022). Alongside the development of new technologies, there is also a focus to develop new technologies, which are able to operate with lower energy costs, or higher efficiency than the existing storage. These have been discussed in more detail in the technology section of the report.

6.2.2 UK CCUS Research Networks Discussion

The research co-ordination and communication institutes provide important forums for academics to interact and share research, as well as opportunities to identify areas of future research, or current limitations. These are discussed in the research networks section. The UKCCSRC currently has more than 1400 members, and both coordinates some funding in the area and identifies gaps. This linkage between different areas of research allows greater collaboration between research, and research that can adapt to developments across the field. The SCCS centre provides similar coordination across Scottish research, and the IEAGHG R&D programme also allows for similar collaboration.

The networks are also important in providing international links such as through the ACT programme, which has enabled UK participation in international research partnerships. This network has included interactions between UK and Indian institutions such as though the SCOPE (Sustainable OPEration of post-combustion Capture plants) project (ACT, website accessed April 2022).

7 India Research Landscape Result and Discussion

7.1 India Research Landscape Results

7.1.1 India CCUS Research Projects Results

During this study, 27 Indian universities were identified as working in CCUS research. Most of these universities are involved in research into carbon capture and utilisation, focussing on pathways for the energy and industrial sectors, whilst fewer universities are researching CO_2 storage and transport ((Figure 11).

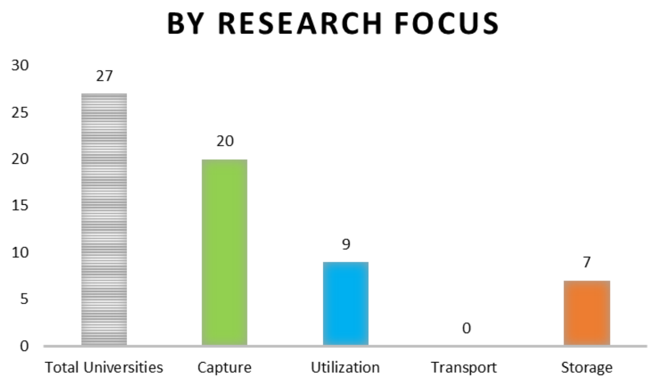


Figure 11: India universities by research focus

Project Name	Technology Name	Leading Participants	Supported By	Year
Hierarchical porous Covalent Organic Nanosheets and Nanosheet –based Hybrid Membranes for Carbon capture and of CO_2 Separation.	Capture	Dr. Rahul Banerjee, Indian Institute of Science Education and Research Kolkata, Pune	DST, India	2019-20
Development of methods for Utilisation and conversion of Waste CO_2 to Fuels.	Utilisation	Dr. Nandini Devi, CSIR-National Chemical Laboratory, Pune	DST, India	2019-20
Demonstration of 10,000 L/day syngas generation unit via Dry reforming	Utilisation	Dr. Ankur Bodoia, CSIR-Indian Institute of Petroleum, Dehradun	DST, India	2019-20
Development of Integrated technologies for reduction of anthropogenic / industrial waste CO_2 to value added Chemicals and Fuels	Utilisation	Dr. Sebastian C. Peter Jawaharlal Nehru Centre for Advanced Science Research (JNCASR), Bangalore, India.	DST, India	2019-20

A systematic large-scale assessment for potential of CO_2 enhanced oil and natural gas recovery in key sedimentary basins in India	Storage	Dr. Vikram Vishal, IIT Bombay	DST, India	2019-21
Development of hierarchical Catalyst for one pot Conversion of CO_2 rich synthesis gas to Dimethyl ether and scale-up Studies.	Utilisation	Prof. Kamal Kishore Pant, Indian Institute of Technology, New Delhi.	DST, India	2019-20
Adsorption and separation of CO_2 by porous carbon obtained from agro-residues and advanced micro porous materials through cost-effective, clean energy methodology.	Capture	Dr. Subarna Maiti, CSIR – Central salt & Marine Chemicals Research Institute, Bhavnagar	DST, India	2019-20
Integrated CO_2 absorption and conversion to methanol in slurry phase reactors using metal complexes as catalyst.	Utilisation	Dr. Sreedevi Upadhyayula Professor, Department of Chemical Engineering, Indian Institute of technology Delhi	DST, India	2019-21
Development of hybrid multi electrode plasma reactor for energy efficient dry reforming of greenhouse gases.	Capture	Dr. Yugeswaran Subramaniam Pondicherry University (Central University), Pondicherry	DST, India	2019-20
Structure, Interaction and process for energy efficient CO_2 separation using Novel Ionic Liquids Supported Membranes	Capture	Dr. Swapnil Dharaskar Pandit Deendayal Energy University, Gujarat	DST, India	2019-20
Study on new green CO_2-Capturing Solvents	Capture	Dr. Prakash D. Vaidya Institute of Chemical Technology, Mumbai	DST, India	2019-20
Model Based Design, Synthesis and Evaluation of Combined sorbent catalyst Material (CSCM) for CO_2 Capture.	Capture	Dr. Yarasi Soujanya CSIR-Indian Institute of Chemical Technology, Hyderabad	DST, India	2019-20
Nano engineered Inorganic Halide Perovskites for photo, Electro and	Capture	Dr. Shravanti S Joshi, Marathwada Institute of	DST, India	2019-20

Thermochemical (PETC) CO_2 Reduction: Novel Artificial Photosynthesis Implementation for Clean Energy Generation.		Technology (MIT-E), Aurangabad		
Development of catalysts and a prototype device for conversion of CO_2 to fuels / Chemicals.	Utilisation	Dr. Arindam Sarkar, Indian Institute of Technology, Bombay	DST, India	2019-20
Development of low cost, efficient and scalable materials for CO_2 captures using naturally available nontoxic stable materials and industrial solid wastes.	Capture	Dr. Chinmay Ghoroi, Indian Institute of Technology Gandhinagar, Gandhinagar	DST, India	2019-20
Studies on CO fuels self-sustaining Unmixed Combustion (UMC) reactor for integrated CO_2 capture and power/ Steam generation.	Capture	Dr. Srinivas Krishnaswamy, BITS Pilani K K Birla, Goa Campus	DST, India	2019-20
Development of agro-mechanical model for CO_2 injection and methane release through experimental studies of matrix shrinkage /swelling, mechanical properties, and permeability of coals.	Storage	Dr. Pratik Dutta, Indian Institute of Engineering Science and Technology, Shibpur	DST, India	2019-20
Investigation of High-Frequency, High-Intensity Ultrasonics for Carbon-Rich Solvent Regeneration in Solvent-Based Post-Combustion CO_2 Capture Process (PCCC) for Reducing CO_2 Capture Energy Demand	Capture	Dr. B. Ambedkar, SSN College Of Engineering, Chennai	DST, India	2019-20
Nano-Encapculation Driven Synergies Activation of carbon Diaoxide into Fuel	Utilisation	Dr. Somenath Garai, BHU, Varanasi	DST, India	2019-2020
Stress history and reservoir pressure for improved	Storage	Dr. Devendra Narain Singh, Indian Institute of Technology Bombay	DST, India	2021-22

quantification of storage containment risks (SHARP)				
Sustainable OPEration of post-combustion Capture plants (SCOPE)	Capture	Prof. N. C. Gupta, GGIP University	DST, India	2021-22
Sequestration of CO2 with Simultaneous Production of Succinic Acid by metabolically engineering	Utilisation	Dr. Bawari Lal, The Energy and Resource Institute , New Delhi	DBT, India	2019-20
Integrated Design and Demonstration of Intensified CO2 capture with cost effective advanced process (INDIA-CO2)	Utilisation	Dr. Sukanta Kumar Dash, Pandit DeenDayal Petrolium University , Gandhinagar, Gujrat	DBT, India	2019-20
Bioconversion of CO2 to biofuels through Microbial Catalyzed Strategies	Utilisation	Dr. G. Velvizhi , Vellore Institute of Technology (VIT) Vellore.	DBT, India	2019-20
Assessment of geomechanical Risks in CO2 enhanced oil recovery & Storage (ARCS)	Utilisation & Storage	Prof. Vikram Vishal, Prof. Bharath Sekhar and Prof. Sudipta Dasgupta, , IIT Bombay	MoPNG, India	2022
Development of a tri-modular CCUS technology based on bio-inspired CO2 activating catalysts	Capture and Utilization	Prof. Arnab Dutta, Prof. D. Maiti and Prof. Vikram Vishal, IIT Bombat	MoPNG, India	2022-23

This is a summary of Table 2.1 which can be found in the accompanying spreadsheet (Appendix 1, links to each university are included.

Many of the research outcomes highlight the potential for CCUS deployment in various industrial scenarios, enhanced coalbed methane recovery, electricity generation and enhanced oil recovery through possible pilot projects (Table 2.1).

Numerous studies have been done on amine-based capture to study their performance and cost optimization (Singh et al., 2017). IIT Delhi successfully developed a novel and economic catalyst for higher conversion levels of syngas rich in CO_2 where a pressure swing adsorption column has been successfully designed and developed in-house for CO_2 capture studies. CSIR, IICT has designed a dual, fixed cum fluidized bed reactor system based on theoretical calculations and carried out preliminary experimental studies. This reactor will be used for testing the new dual functional materials with combined catalytic activity and carbon capture synthesized for SESMR application.

Recently, scientists at IISER, Kolkata have demonstrated a method to synthesize a novel solid adsorbent. They discovered nanoparticles for capturing carbon in their micro and mesoporous voids. These nanoparticles include covalent organic frameworks (COF)-coated zeolites and graphene which could be excellent for CO_2 storage in the industry due to their increased chemical stability and high surface area (Mohata, Shibani, et al., 2021).

Rajiv Gandhi Proudyogiki Vishwavidyalaya (RGPV), Bhopal developed a post combustion carbon capture and sequestration pilot plant in Bhopal for carbon capture and conversion into hydrogen, methane, and algae. Hydrogen could be used in fuel cell application, methane for methane-based turbines for power generation and algae for biodiesel (Sethi, V.K. and Vyas, S., 2017). Apart from academia, industries also conducted research on carbon capture feasibility in power plants. NTPC and BHEL have done multiple studies on implementing capture framework in existing large power plants (Kumar et al., 2019). The Oxy-fuel tests have been carried out successfully at the Coal Research Centre's Solid Fuel Burning Test Facility at Bharat Heavy Electricals Limited (BHEL), Trichy under the EU TREC-STEP BHEL CCT CCS project, with encouraging results.

There has been significant research on CO_2 utilisation in India. Enhanced Oil Recovery and Enhanced Coal Bed Methane Recovery remain the preferred choice based on their scalability and deployments. IIT, Bombay and NGRI, Hyderabad have conducted feasibility studies in two coal fields in Eastern India. However, the preliminary studies show that the availability of the depleted oil and gas basins (category 1) in Cambay, Assam shelf, Mumbai offshore, Krishna- Godavari, Cauvery and Rajasthan provide significant potential for CO_2 EOR. Initial feasibility studies on Cambay basin have shown 10% tertiary oil recovery and 150Mt CO_2 storage potential (Vishal, Verma, *et al.*, 2021)

Other utilisation pathways include production of hydrogen, methane, methanol, syngas, polymers, microalgae, cement curing etc. are also being studied for various energy intensive sectors. A simulation study conducted by NIT, Warangal on CO_2 utilisation in the form of formic acid synthesis using the captured CO_2 to produce high concentration of H_2 from a Coal Direct Chemical Looping (CDCL) plant. The results revealed utilisation of 62.49 kg.CO_2/GJ of fuel input (Surywanshi, Gajanan Dattarao, et al, 2019). Few studies have been performed on the production of synthetic natural gas from CO_2 using membrane reactors. Similar research has been conducted on the production of methane, methanol, and dimethyl ether DME. (Anwar *et al.*, 2020). Market research has shown an annual growth of 6% in the soda ash market, where the CO_2 capture costs could be offset at a market price of less than $20/t of product (Vishal, Verma, *et al.*, 2021). And a list of Indian reservoirs has been identified and proposed for SHS (Subsurface H2 Storage) (Joshi et. Al, 2022).

Utilisation methods for conversion to methanol have also been promoted by the Indian stakeholders with an estimated utilisation potential of 10-12 Mt/year. The LCA of this utilisation pathway shows a positive outlook for net-zero emissions when coupled with power plants (Hoppe et al.,2018). Methanol is a low carbon, alternative energy option produced from high ash coal, CO_2 from thermal power plants, municipal solid waste and natural gas. Renewable methanol can also be produced from agricultural residues, landfill gas and atmospheric CO_2. Blending 15% of methanol in gasoline can result in 15% reduction of oil import and also reduce the emissions by 20% in terms of particulate matter, Nox, and Sox. It could also be substituted with petrol or diesel for various uses like transport (road, rail, marine), energy sector (boilers, process heating modules, tractors and commercial vehicles), cooking (replacing LPG, kerosene and wood charcoal). Niti Ayog's "Methanol

Economy program" has been running to reduce oil and gas imports, improve energy security and promote economic development. It aims to create 5 million jobs through the production, application and distribution services. Hence, the CO_2 utilisation to methanol shows a long term clean-energy transition.

There has been significant research done on the developing theoretical and effective CO_2 storage capacities for different geological formations in India. Various research has estimated the total storage capacity ranges between 395 – 614 Gt of CO_2, which is distributed among storage in oil fields (3.4 Gt), coal formations (3.7 Gt), deep saline aquifers (291 Gt), and basalts (97–316 Gt). (Vishal et al., 2021). A preliminary study estimated potential storage of 395-614Gt is feasible under various scenarios like energy and environmental policies, decentralized cogeneration and Indian CO_2 emission reduction regime. India has some of the world's largest sedimentary basins, around 29 of them. They have been classified into three categories based on recoverable hydrocarbon sources. Category 1 has a considerable amount of recoverable hydrocarbon, with abundant data, crucial for CCUS operations. Category 2 basins are subeconomic with future potential for recovery and CCUS. Category 3 basins are the least developed and have limited data for now, with future potential of storage.

Enhanced Oil Recovery (EOR) has been a focus area for research owing to its feasibility, scalability and economic viability. A theoretical capacity of 3402 Mt of CO_2 storage potential has been estimated through EOR. Current collaboration include British Geological Survey (BGS), IIT Bombay and (NGRI), who are already working on assessment for potential of CO_2 enhanced oil and natural gas recovery in Cambay Basin under a Containment risk Mitigation in Indian CO_2 Storage (COMICS) project. It will establish the feasibility of scaling up from pilot project, define geological containment, and determining storage constraint. This is an ongoing project expected to complete soon (2022). IOCLs' Koyali refinery is expected to supply CO2 for EOR to ONGC and initial studies have been completed, with the help of Dastur and Toyo Engineering India Private Limited.

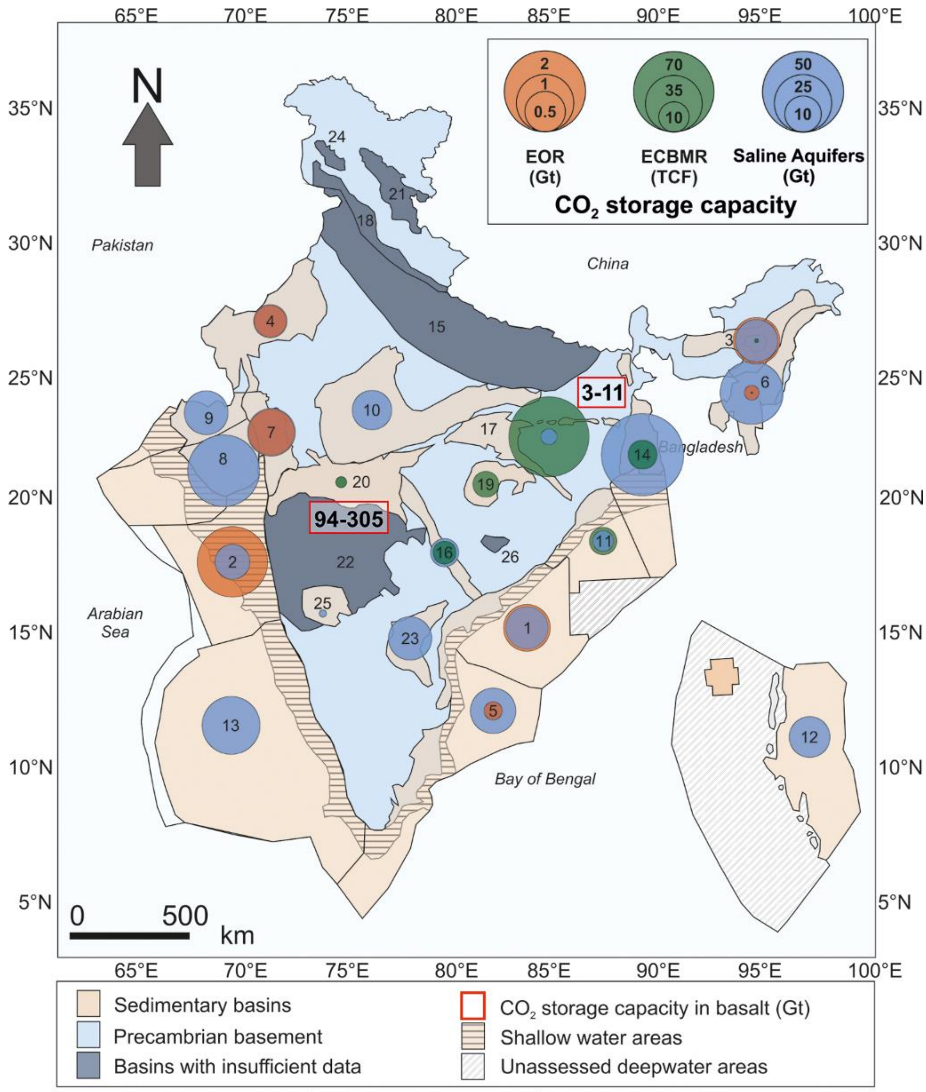
The total coal reserves in India is estimated to grow by 369.6 Mt by 2030, providing a storage capacity of 4.02 Gt of CO_2. The Indian coal belts are also being studied estimating a potential of 2.8-3.5 Gt as coal bed methane reserves. (Sharma, Vishal and Singh, 2017; Varma *et al.*, 2015). The coal bed methane reserves in the basins of Satpura-south Rewa-Damodar, Bengal Purnea and Chhattisgarh highlighted high CO_2 storage potential. (Vishal, Verma, *et al.*, 2021)

The basalt formations of the Deccan volcanic province is being studied for storage feasibility. Including a theoretical estimation of 94-305 Gt of carbon storage capacity. Evaluation of the basalt formation for long term carbon storage was carried out by National Geophysical Research Institute (NGRI) and Battelle Pacific Northwest National Laboratory, USA with encouraging outcomes. A recent study by IIT, Bombay also classified and created a systematic assessment of various methods to estimate the storage in different geological formations. Funded by the European CCUS Research Infrastructure Support, NGRI is also conducting a large-scale project in understanding the physical properties and seismic attenuation of Deccan Basalts under the CO_2 injection. However, there is still a lack of data on storage mechanisms in Indian context.

The category 1 basins of Assam– Arakan belt, Cambay, Cauvery, Mumbai offshore, Rajasthan provide high potential of CO_2 storage of 108.6 Gt approx. Assam Arakan belt has a large potential of 30 Gt of storage. The Ganga Basin has a large theoretical storage capacity of 80Gt based on its geology

Research remains limited in understanding accurate map of the sinks in India. Limited information is available on the basalt formations, deep saline aquifers and deep coal seams, hence providing an opportunity to consider long term analysis, assessment of ecological, economical and resource strategic challenges (P. Viebahn et al., 2010)

Figure 12 below taken from recent research from IIT, Bombay provides a mapping of the storage potential of various geological formations.



Category-I basins	Category-II basins	Category-III basins
1. Krishna-Godavari	8. Saurashtra	13. Kerala-Konkan
2. Mumbai Offshore	9. Kutch	14. Bengal-Purnea
3. Assam-Shelf	10. Vindhyan	15. Ganga-Punjab
4. Rajasthan	11. Mahanadi	16. Pranhita-Godavari
5. Cauvery	12. Andaman	17. Satpura-South Rewa-Damodar
6. Assam-Arakan Fold belt		18. Himalayan Foreland
7. Cambay		19. Chhattishgarh
		20. Narmada
		21. Spiti-Zanskar
		22. Deccan Syncline
		23. Cuddapah
		24. Karewa
		25. Bhima-Kaladgi
		26. Bastar

Figure 12: Map of Indian Carbon storage potential (IIT Bombay) Vishal et al., 2021, A systematic capacity assessment and classification of geologic CO2 storage systems in India. International Journal of Greenhouse Gas Control, Vol. 111, p.103458.

7.1.2 India CCUS Research Networks Results

India has joined several national and international platforms for enhancing research and development (R&D) capabilities and dissemination of technology (Table 2.2). The Indian CO_2 Sequestration Applied Research (ICOSAR) Network was established earlier by DST, India to lead the R&D efforts. The Indian research network has also engaged with international forums like big sky CCS partnership, Asia Pacific Partnership for Clean Development and Climate, US FutureGen project, International Partnership for a Hydrogen

Economy (IPHE) and Carbon Sequestration Leadership Forum at multiple levels. India is also supported by The European CCUS Research infrastructure, a European Research Infrastructure Consortium (ECCSEL ERIC) on storage research. BGS has been a research partner with DST for long time, with past joint studies on CCUS. Following is the list of the key research networks driving the CCUS development in India.

Research Network Name	Description of Research Activity
Mission Innovation	Mission Innovation (MI) is a global initiative catalysing a decade of action and investment in research, development and demonstration to make clean energy affordable, attractive and accessible for all. This will accelerate progress towards the Paris Agreement goals and pathways to net zero. India had supported the proposals under Innovation Challenge (IC#3) to undertake joint Research & Development with member MI countries to identify and prioritize breakthrough technologies in the field of CO2 Capture, Separation, storage and value addition.
Accelerating CCS Technologies (ACT)	ACT is a global CCS research funding group, originally designed to run from 2016-21, but has since been extended under ACT3 – including funding from both UK and India, among others.Under ACT 3 call DST has supported two multilateral Consortia projects with 5 ACT member countries with UK being part of the consortia. DST, India is also participating in ACT4 call.
European CCUS Research infrastructure ECCSEL ERIC	ECCSEL is the European Research Infrastructure for CO_2 Capture, Utilisation, Transport and Storage (CCUS). They are supporting CCS projects in India.
Asia Pacific Partnership for Clean Development and Climate	The partnership established eight public-private sector Task Forces in cleaner fossil energy, power generation, steel, cement and coal to address energy security and climate change mitigation

This is a summary of Table 2.2 which can be found in the accompanying spreadsheet (Appendix 1).

7.2 India CCUS Research Landscape Discussion and Insights

7.2.1 India CCUS Research Projects Discussion

Research and Development has been strengthened by collaboration and partnership with various institutions globally. Led by DST, CCUS has been a clear focus area of development in India, in capture, utilisation and storage technology. India has identified carbon capture, utilisation and storage as priority area for future research. Successful research projects under Mission Innovation (MI) and the ACT initiative have also placed India at a strong position to further advance the research in improving the technology readiness and feasibility analysis. There has been strong collaboration between India and other countries in advancing the CCUS research including in the areas of CCUS technologies under Indo-US strategic energy partnership in 2020. There are also ongoing collaboration projects with BGS and the European CCUS Research infrastructure, (ECCSEL ERIC) on carbon storage research.

Through TIFAC, an autonomous body under DST, a roadmap for CCUS in India was established in 2018, focusing on the necessary steps leading to increased implementation of CCUS technology. When the roadmap was published, there were no ongoing CCUS projects at a demonstration level. The report noted that for growth in the Indian CCUS sector, stakeholders should focus on creating a dedicated central body for CCUS, identifying carbon sources and sinks, promoting the development of TEA and LCA reports, financial planning of CCUS projects, and following up with a detailed roadmap for CCUS in India (TIFAC, 2018). While the central body has not been established for all CCUS activities in India, the increase in the capacity studies, TEA, LCA, and overall support from DST in research and implementation has led to multiple demonstration projects within research networks as well as in many Indian industries that use Indian – based CCUS technology.

R&D in India has also led to some successful start-ups, like Breathe Sciences (JNCASR). More start-ups and innovations are intended to be supported through various institutional initiatives and schemes.

IIT-Bombay has been involved in several projects across the CCUS domain and has recently been felicitated for its successful demonstration of CO_2 removal through a tri-modular CO_2 capture, conversion and storage system for which it won a $250,000 grant from the Xprize, in association with the Musk Foundation.

The various areas of carbon capture, utilisation and storage are being extensively studied and there is overlap with the with the UK's research objectives. Based on the research landscape in both the countries, there are collaboration opportunities in the areas of capture, utilisation and storage.

7.2.2 India CCUS Research Networks Discussion

The Indian CCUS research networks have been evolving for the last ten years. Through various on-going partnerships and collaborations, the network is expanding CCUS research across various dimensions of capture, utilisation and storage. The various partnerships are also instrumental in enabling the capacity building and best practices sharing across the network. They are also going to be critical in accessing the funding for CCUS research in the long run. India's partnership with US, UK and EU will also place the CCUS in the mainstream of net-zero objectives for those countries.

8 Conclusions

There are a range of potential areas of collaboration in research between the UK and India on CCUS. These include CO_2 Capture Technologies, CO_2 Utilisation, CO_2 Storage, and through cross cutting collaboration. The governments reaffirmed their commitment to collaboration during the UK Prime Minister's visit to India in April 2022, in climate technology deployment and R&D through the joint statement (Prime Minister's Office, 2022).

Both countries are seeking to develop and deploy CCUS technologies as part of their national commitments to reach net zero, and face some similar obstacles. Collaboration and shared expertise could accelerate this process, as well as providing an opportunity to leverage the extensive academic experience and research facilities in the UK and India.

8.1 CO_2 Capture

Reducing the energy penalty and cost of CO_2 capture has been a common interest for R&D activity so far in India and the UK. Improving efficient and cost-effective capture is important for both CO_2 utilisation and permanent geological storage. So far R&D has resulted in the development of improved amines, novel solvents and adsorbents in both countries, and this is an ongoing area of research. There is successful existing India – UK collaboration in this field; Carbon Clean has developed CO_2 capture technology in the UK which is already deployed at a commercial CO_2 utilisation project for Tuticorin Alkali Chemicals and Fertilizers in India.

Innovators in India and UK could collaborate at both high and low TRLs, to develop further improvements in CO_2 capture technology. At high TRLs there are opportunities for ongoing reductions in energy usage in existing technologies, the field testing and further scale up of emerging new solvents, heat exchangers and modular approaches to CO_2 capture.

At lower TRLs, DAC technologies are also at an early stage in both the UK and India, as well as the use of new polymer materials to replace corrosion resistant steel, and the continued development of non-amine solvents and adsorption technologies.

There are opportunities for early deployment of new technologies, particularly as part of the large scale CCUS projects in development in the UK, targeting completion in the mid-2020s, and the emerging CO_2 utilisation market in India.

8.2 CO_2 Utilisation

In the UK and India there is significant common interest in CO_2 utilisation technologies where there is either or both, a strong cost advantage or a high degree of permanent and secure CO_2 storage.

CO_2 conversion to mineral carbonates that may be used as chemical feedstocks or building materials represents a strong potential for collaboration between India and the UK. Such processes can achieve a high degree of permanent and secure CO_2 storage, depending on the end use. UK CO_2 utilisation technology start-up Carbon8, and India chemicals business Tuticorin Alkali Chemicals and Fertilizers are both innovators in this space.

A further area of potential collaboration exists in CO_2 conversion to high value products, such as jet fuel, DME (via methanol) or certain polymers. In this case there may be strong cost advantage derived from life-cycle CO_2 emissions benefits from these products. A low-carbon and cost effective source of hydrogen is typically required for these processes and that also represents a complimentary target for innovation collaboration, which has been announced during the recent UK Prime Minister's visit to India.

The CO_2 utilisation field is broad and rich with opportunities for collaboration across the TRL range, from discovery of new materials and processes through lab testing and field testing to scale-up for commercial projects.

8.3 CO_2 Transport and Storage

The characterisation of CO_2 storage resource and quantification of reserves capacity has previously been an area of collaboration between the UK and India and has the potential for further future collaboration.

The COMICS project is an example of this collaboration, involving the British Geological Survey (BGS), the Indian Institute of Technology Bombay (IITB) and, the National Geophysical Research Institute (NGRI). This project, focused on quantifying storage in the Cambay Basin, could in principle be extended to cover other prospective basins for CO_2 storage in India. The safety aspects of this project, demonstrating the ongoing security of storage in local geologies and developing monitoring and safety best practices could be another ongoing area for shared research.

The UK has previously developed an extensive understanding of where and how much CO_2 could be stored and what the economics of CO_2 storage in different settings would be in the UK. The majority of this potential storage is located in deep saline formations offshore with also significant potential in depleted oil and gas fields. This has been a driver for CCUS policy incentives in the UK, and the resulting engagement of project developers to develop CO_2 transport and storage elements of CCUS projects.

In India work has been undertaken to begin to quantify CO_2 storage opportunities. Potential exists for storage associated with CO_2 EOR and CO_2 ECBMR, and similar to the UK, the potential also exists in depleted oil and gas fields and also in deep saline formations. There are opportunities for less conventional storage in or using rock quarried from extensive basalt formations.

Potential collaboration on CO_2 storage resource characterisation, reserves capacity and economics could be carried out in collaboration possibly using methods and tools developed for the UK combined with the data and knowledge of the geology of India. This could be used to produce an atlas for Indian CO_2 storage which could feed into modelling the lowest cost storage locations when combined with emission data and locations.

If required, Indian and UK collaboration could be extended to develop knowledge of overburden properties and fluid migration processes and the development of monitoring technologies specifically for Indian geological settings.

There is also an opportunity for collaboration of CO_2 transport technologies, especially shipping CO_2, which may offer access for both countries to storage location outside the domestic geographies. This technology is mature, but is currently at small scale, so there are opportunities in both countries for this to be developed to a larger scale.

8.4 Cross-Cutting CCUS Collaboration

There are several areas of cross-cutting CCUS activity where there is significant opportunity for India – UK collaboration on the technical R&D areas of capture, utilisation and storage.

These include the development of energy systems analysis, looking at the whole energy system to identify the role that CCUS can play in meeting national emissions reduction plans, and the impact of CCUS on other areas of the energy system. This could identify which industrial sectors might benefit most from CCUS and where trade-offs might exist. This analysis could then inform the design and further development of regulations and policy incentives to created effective market mechanisms to ensure that CCUS developments are realised safely and effectively.

This wider systems analysis could include the development of conceptual CCUS projects, including identification of hubs or clusters of projects to leverage economies of scale and catalyse commercial project development.

The impact beyond the energy system, including the wider economic and social impact of CCUS, is a further area with potential opportunities for the UK and India to collaborate on in helping to inform policy makers, maximise benefits, and ensure social license to operate for CCUS technologies. This could include the identification of any negative side impacts, such as flue emissions or impacts on biodiversity, as well as the economic benefits.

8.5 Routes to Collaboration

UK and India have been already engaged in collaboration across scientific R&D more broadly via the Newton-Bhabha MoU on UK-India Science and Technology cooperation and specifically on CCUS via Mission Innovation, which started in 2018. There has also been previous collaboration via Containment risk Mitigation in Indian CO_2 Storage (COMICS) project in Storage funded by NERC and CO_2 injection for Enhanced Oil Recovery in the Cambay Basin in India which was completed in March 2022 (the results are currently pending). The UK and India have also both been members of the ACT programme.

There is a range of routes through which further future research collaboration could be carried out. This could include the development of links between research networks and centres of excellence in each country. This could leverage existing links between academics and could potentially facilitate joint conferences or research programmes. For example, there could be collaboration between the Indian CCUS Centres of Excellence, and UK networks such as the UKCCSRC.

There is also the opportunity for later stage collaboration to take place between SMEs and Industry, to support the piloting or demonstration of technologies.

9 References

ACORN (no date) Acorn Details. Available at: https://www.geos.ed.ac.uk/sccs/project-info/2081 (Accessed: April 22, 2022).

ACT (no date) ACT3. Available at: http://www.act-ccs.eu/act3 (Accessed: April 22, 2022).

Akash, A.R., Rao, A.B. and Chandel, M.K. (2017) "Relevance of Carbon Capture & Sequestration in India's Energy Mix to Achieve the Reduction in Emission Intensity by 2030 as per INDCs," Energy Procedia, 114, pp. 7492–7503. doi:10.1016/J.EGYPRO.2017.03.1882.

Amit Garg, P.R. Shukla, Shrutika Parihar, Udayan Singh, Bhushan Kankal, Cost-effective architecture of carbon capture and storage (CCS) grid in India, International Journal of Greenhouse Gas Control

Anwar, M.N. et al. (2020) "CO_2 utilization: Turning greenhouse gas into fuels and valuable products," Journal of Environmental Management, 260, p. 110059. doi:10.1016/J.JENVMAN.2019.110059.

Behera, B., Aly, N. and Paramasivan, B. (2020) "Theoretical Modeling of Algal Productivity and Carbon Capture Potential in Selected Places of Odisha, India," Journal of The Institution of Engineers (India): Series A 2020 101:3, 101(3), pp. 503–512. doi:10.1007/S40030-020-00450-8.

British Geological Survey (2021) SCIENCE CASE FOR CO_2 STORAGE LABORATORY.

British Geological Survey (no date a) Carbon capture and storage - British Geological Survey. Available at: https://www.bgs.ac.uk/geology-projects/carbon-capture-and-storage/ (Accessed: April 22, 2022).

British Geological Survey (no date b) CO_2 Stored Homepage. Available at: https://www.co2stored.co.uk/home/index (Accessed: April 22, 2022).

Bui, M., Adjiman, C.S., Bardow, A., Anthony, E.J., Boston, A., Brown, S., Fennell, P.S., Fuss, S., Galindo, A., Hackett, L.A., Hallett, J.P., Herzog, H.J., Jackson, G., Kemper, J., Krevor, S., Maitland, G.C., Matuszewski, M., Metcalfe, I.S., Petit, C., Puxty, G., Reimer, J., Reiner, D.M., Rubin, E.S., Scott, S.A., Shah, N., Smit, B., Trusler, J.P.M., Webley, P., Wilcox, J., Mac Dowell, N., 2018. Carbon capture and storage (CCS): the way forward. Energy Environ. Sci. 11, 1062–1176. https://doi.Org/10.1039/c7ee02342a

Cambridge Econometrics and AFRY (2021) "ECONOMIC ANALYSIS OF UK CCUS A report to Carbon Capture and Storage Association."

Capturing Carbon and a Global Opportunity CCUS Investor Roadmap (2022).

CCSA (no date) Home - CCSA. Available at: https://www.ccsassociation.org/ (Accessed: April 22, 2022).

Chaturvedi, Vaibhav, and Ankur Malyan. 2021. Implications of a Net-Zero Target for India's Sectoral Energy Transitions and Climate Policy. New Delhi: Council on Energy, Environment and Water

CO_2Chem (no date) CO_2Chem - The Carbon Dioxide Utilisation Network. Available at: http://co2chem.co.uk/ (Accessed: April 22, 2022).

Cranfield University (no date) Carbon Capture and Transport. Available at: https://www.cranfield.ac.uk/academic-disciplines/carbon-capture-and-transport (Accessed: April 22, 2022).

Department for Business, E.& I.S. (2022 a) Cluster sequencing Phase-2: eligible projects (power CCUS, hydrogen and ICC). Available at: https://www.gov.uk/government/publications/cluster-sequencing-phase-2-eligible-projects-power-ccus-hydrogen-and-icc/cluster-sequencing-phase-2-eligible-projects-power-ccus-hydrogen-and-icc (Accessed: April 22, 2022).

Department for Business, E.& I.S. (2022 b) Projects selected for Phase 1 of the Direct air capture and greenhouse gas removal programme - GOV.UK. Available at: https://www.gov.uk/government/publications/direct-air-capture-and-other-greenhouse-gas-removal-technologies-competition/projects-selected-for-phase-1-of-the-direct-air-capture-and-greenhouse-gas-removal-programme (Accessed: April 22, 2022).

Department for Business Energy & Industrial Strategy (2018) CO_2 Shipping Study Final Report for BEIS.

Department for Business Energy & Industrial Strategy (2021 a) Carbon Capture, Usage and Storage (CCUS) Innovation 2.0 competition: guidance and how to apply - GOV.UK. Available at: https://www.gov.uk/government/publications/ccus-innovation-20-competition (Accessed: April 22, 2022).

Department for Business Energy & Industrial Strategy (2021 b) Cluster sequencing for carbon capture, usage and storage (CCUS) deployment: Phase-1 - GOV.UK. Available at: https://www.gov.uk/government/publications/cluster-sequencing-for-carbon-capture-usage-and-storage-ccus-deployment-phase-1-expressions-of-interest (Accessed: April 22, 2022).

Department Of Science & Technology (2021) Indias first pilot plant to convert high ash coal to methanol can accelerate the country's journey towards clean technology, Department Of Science & Technology. Available at: https://dst.gov.in/indias-first-pilot-plant-convert-high-ash-coal-methanol-can-accelerate-countrys-journey-towards (Accessed: April 4, 2022).

Dey, K. et al. (2020) "Nanoparticle Size-Fractionation through Self-Standing Porous Covalent Organic Framework Films," Angewandte Chemie, 132(3), pp. 1177–1181.

Drax (no date) BECCS and negative emissions - Drax Global. Available at: https://www.drax.com/about-us/our-projects/bioenergy-carbon-capture-use-and-storage-beccs/ (Accessed: April 22, 2022).

Drax (2019) Carbon dioxide now being captured in first of its kind BECCS pilot - Drax Global. Available at: https://www.drax.com/press_release/world-first-co2-beccs-ccus/ (Accessed: April 22, 2022).

Drax (2021) Drax and Mitsubishi Heavy Industries sign pioneering deal to deliver the world's largest carbon capture power project - Drax Global. Available at: https://www.drax.com/press_release/drax-and-mitsubishi-heavy-industries-sign-pioneering-deal-to-deliver-the-worlds-largest-carbon-capture-power-project/ (Accessed: April 22, 2022).

Drax (2020) Negative emissions pioneer Drax and leading global carbon capture company - Mitsubishi Heavy Industries Group - announce new BECCS pilot - Drax Global. Available at: https://www.drax.com/press_release/negative-emissions-pioneer-drax-and-leading-global-carbon-capture-company-mitsubishi-heavy-industries-group-announce-new-beccs-pilot/ (Accessed: April 22, 2022).

ETI (no date) Carbon Capture and Storage | The ETI. Available at: https://www.eti.co.uk/programmes/carbon-capture-storage (Accessed: April 22, 2022).

Garg, A. et al. (2017) "Cost-effective architecture of carbon capture and storage (CCS) grid in India," International Journal of Greenhouse Gas Control, 66, pp. 129–146. doi:10.1016/J.IJGGC.2017.09.012.

Ganguly, D. et al. (2018) "Valuing the carbon sequestration regulation service by seagrass ecosystems of Palk Bay and Chilika, India," Ocean & Coastal Management, 159, pp. 26–33. doi:10.1016/J.OCECOAMAN.2017.11.009.

GeoEnergy Research Centre (no date) GERC Facilities. Available at: http://www.gerc.ac.uk/facilities/facilities.aspx (Accessed: April 22, 2022).

Gibbins, J. and Lucquiaud, M. (2021) BAT Review for New-Build and Retrofit Post-Combustion Carbon Dioxide Capture Using Amine-Based Technologies for Power and CHP Plants Fuelled by Gas and Biomass as an Emerging Technology under the IED for the UK Ver.1.0. Available at: https://ukccsrc.ac.uk/best-available-technology-bat-.

Global CCS Institute (2021) Technology Readiness and Costs of CCS.

Gough, C. and Mander, S. (2019) "Beyond Social Acceptability: Applying Lessons from CCS Social Science to Support Deployment of BECCS," Current Sustainable/Renewable Energy Reports, 6(4), pp. 116–123. doi:10.1007/S40518-019-00137-0.

Gupta, A. and Paul, A. (2019) "Carbon capture and sequestration potential in India: A comprehensive review," in Energy Procedia. Elsevier Ltd, pp. 848–855. doi:10.1016/j.egypro.2019.02.148.

HM Government (2021) Net Zero Strategy: Build Back Greener. Available at: https://www.gov.uk/government/publications/net-zero-strategy (Accessed: April 6, 2022).

HM Government (2022) North Sea Transition Deal: one year on. Available at: https://www.gov.uk/government/publications/north-sea-transition-deal (Accessed: April 28, 2022).

Hoppe, W., Thonemann, N., Bringezu, S., 2018. Life Cycle Assessment of Carbon

Dioxide–Based Production of Methane and Methanol and Derived Polymers. J. Ind.

Ecol. https://doi.org/10.1111/jiec.12583

IEA (2019a) Exploring Clean Energy pathways.

IEA (2019b) Putting CO2 to Use Creating value from emissions. Available at: https://iea.blob.core.windows.net/assets/50652405-26db-4c41-82dc-c23657893059/Putting_CO2_to_Use.pdf

IEA (2020) Technology Perspectives Energy Special Report on Carbon Capture Utilisation and Storage CCUS in clean energy transitions. Available at: www.iea.org/t&c/.

IEAGHG (no date) IEAGHG - Home Page. Available at: https://ieaghg.org/ (Accessed: April 22, 2022).

Imperial College London Facilities (no date) | Faculty of Engineering | Imperial College London. Available at: https://www.imperial.ac.uk/chemical-engineering/discovery/facilities/ (Accessed: April 22, 2022).

IEA (2020) Technology Perspectives Energy Special Report on Carbon Capture Utilisation and Storage CCUS in clean energy transitions. Available at: www.iea.org/t&c/.

IRENA And Methanol Institute (2021) Innovation Outlook : Renewable Methanol. Abu Dhabi. Available at: www.irena.org.

Iyer, S., Rao, A.B. and Banerjee, R. (2020) "Techno-Economic Comparison of Coal Plants in India with Conventional and Advanced Power Generation Technologies Integrated with Calcium Looping Based CO_2 Capture," SSRN Electronic Journal [Preprint]. doi:10.2139/SSRN.3365974.

Joshi, Shruti, and Krishna Raghav Chaturvedi. "Exploring the Feasibility of Geological Storage of Hydrogen in Indian Porous Media: Challenges, Opportunities and the Way Ahead." Paper presented at the International Petroleum Technology Conference, Riyadh, Saudi Arabia, February 2022. doi: https://doi.org/10.2523/IPTC-22320-MS

Kelemen, P. et al. (2019) "An Overview of the Status and Challenges of CO_2 Storage in Minerals and Geological Formations," Frontiers in Climate. Frontiers Media S.A. doi:10.3389/fclim.2019.00009.

Kumar, P. et al. (2017) "Post combustion capture and conversion of carbon dioxide using histidine derived ionic liquid at ambient conditions," Journal of Industrial and Engineering Chemistry, 49, pp. 152–157. doi:10.1016/j.jiec.2017.01.022.

Kumar, A. and Shrivastava, J.P. (2019) "Long-term CO_2 capture-induced calcite crystallographic changes in Deccan basalt, India," Environmental Earth Sciences 2019 78:13, 78(13), pp. 1–19. doi:10.1007/S12665-019-8378-X.

Macgillivray, A. and Livesey, H. (2021) "Evaluation of a public dialogue on Carbon Capture Utilisation and Storage (CCUS) Report to BEIS and Sciencewise."

Majoumerd, M.M., Raas, H., Jana, K., De, S., Assadi, M., 2017. Coal quality effects on the performance of an IGCC power plant with CO_2 capture in India. Energy Procedia. Elsevier Ltd, pp. 6478–6489. https://doi.org/10.1016/j.egypro.2017.03.1784.

Malyan, A. and Chaturvedi, V. (2021) Carbon Capture, Utilisation, and Storage (CCUS) in India From a Cameo to Supporting Role in the Nation's Low-Carbon Story Centre for Energy Finance. New Delhi. Available at: https://www.ceew.in/sites/default/files/ceew-study-on-the-role-of-carbon-capture-utilization-and-storage-in-india.pdf (Accessed: March 21, 2022).

Mete, G. et al. (2021) Reaching Net-Zero Industry through Public-Private Partnerships. Available at: https://www.ipcc.ch/site/.

Mohata, S., Dey, K., Bhunia, S., Thomas, N., Gowd, E.B., Ajithkumar, T.G., Reddy, C.M. and Banerjee, R., 2021. Dual Nanomechanics in Anisotropic Porous Covalent Organic Framework Janus-Type Thin Films. Journal of the American Chemical Society.

Mondal, M.K., Balsora, H.K. and Varshney, P. (2012) "Progress and trends in CO_2 capture/separation technologies: A review," Energy, 46(1), pp. 431–441. doi:10.1016/j.energy.2012.08.006.

Müller, L.J. et al. (2020) "A Guideline for Life Cycle Assessment of Carbon Capture and Utilisation," Frontiers in Energy Research, 8, p. 15. doi:10.3389/FENRG.2020.00015/BIBTEX.

National Oceanography Centre (no date) CHIMNEY | National Oceanography Centre. Available at: https://noc.ac.uk/projects/chimney (Accessed: April 22, 2022).

NPL (2021) Energy transition: Measurement needs for carbon capture, usage and storage. Available at: www.npl.co.uk/contact (Accessed: April 22, 2022).

OGCI (2018) "The Potential Value of CCUS to the UK Economy."

Press Information Bureau (2019) Pradhan Mantri Urja Ganga Project, Press Information Bureau. Available at: https://pib.gov.in/Pressreleaseshare.aspx?PRID=1579087 (Accessed: March 16, 2022).

Prime Minister's Office, UK-India joint statement April 2022: Towards shared security and prosperity through national resilience - GOV.UK (2022). Available at: https://www.gov.uk/government/publications/prime-minister-boris-johnsons-visit-to-india-april-2022-uk-india-joint-statements/uk-india-joint-statement-april-2022-towards-shared-security-and-prosperity-through-national-resilience (Accessed: April 26, 2022).

P. Viebahn, A. Esken, S. Höller, H. Luhmann, K. Pietzner, D. Vallentin, RECCS plus - Comparison of Renewable Energy Technologies (RE) with Carbon Dioxide Capture and Storage (CCS). Update and Expansion of the RECCS study. Final Report of Wuppertal Institute on behalf of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Berlin, 2010

Rao, A.B. and Kumar, P. (2014) "Cost implications of carbon capture and storage for the coal power plants in India," Energy Procedia, 54, pp. 431–438. doi:10.1016/J.EGYPRO.2014.07.285.

Ravinder Kumar, Mohammad Hossein Ahmadi, Dipen Kumar Rajak, Mohammad Alhuyi Nazari, A study on CO_2 absorption using hybrid solvents in packed columns, International Journal of Low-Carbon Technologies, Volume 14, Issue 4, December 2019, Pages 561–567, https://doi.org/10.1093/ijlct/ctz051

Realmonte, G. et al. (2019) "An inter-model assessment of the role of direct air capture in deep mitigation pathways," Nature Communications, 10(1). doi:10.1038/s41467-019-10842-5.

Samari, M. et al. (2020) "Direct capture of carbon dioxide from air via lime-based sorbents," Mitigation and Adaptation Strategies for Global Change, 25(1), pp. 25–41. doi:10.1007/S11027-019-9845-0/FIGURES/7.

Sethi, V.K. and Vyas, S., 2017. An innovative approach for carbon capture & sequestration on a thermal power plant through conversion to multi-purpose fuels–a feasibility study in indian context. Energy Procedia, 114, pp.1288-1296.

SCCS (no date) Scottish Carbon Capture & Storage. Available at: https://www.sccs.org.uk/ (Accessed: April 22, 2022).

Shell (no date) Cansolv SO_2 Scrubbing System | Sulphur Dioxide Removal | Shell Catalysts & Technologies | Shell Global. Available at: https://www.shell.com/business-customers/catalysts-technologies/licensed-technologies/emissions-standards/tail-gas-treatment-unit/cansolv.html (Accessed: April 22, 2022).

Singh, M., Borkhatariya, N., Pramanik, P., Dutta, S., Ghosh, S.K., Maiti, P., Neogi, S. and Maiti, S., 2022. Microporous carbon derived from cotton stalk crop-residue across diverse geographical locations as efficient and regenerable CO_2 adsorbent with selectivity. Journal of CO_2 Utilization, 60, p.101975.

Singh, U., Rao, A.B. and Chandel, M.K. (2017) "Economic Implications of CO_2 Capture from the Existing as Well as Proposed Coal-fired Power Plants in India under Various Policy Scenarios," Energy Procedia, 114, pp. 7638–7650. doi:10.1016/J.EGYPRO.2017.03.1896.

Surywanshi, G.D., Pillai, B.B.K., Patnaikuni, V.S., Vooradi, R. and Anne, S.B., 2019. Formic acid synthesis–a case study of CO_2 utilization from coal direct chemical looping combustion power plant. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, pp.1-16.

Styring, P. and Dowson, G.R.M. (2021) "Oxygenated transport fuels from carbon dioxide," Johnson Matthey Technology Review. Johnson Matthey Public Limited Company, pp. 170–179. doi:10.1595/205651321x16063027322661.

SWIC (2022) SWIC | South Wales Industrial Cluster. Available at: https://www.swic.cymru/ (Accessed: April 22, 2022).

Tata Chemicals (no date) Carbon Capture & Utilisation | Tata Chemicals. Available at: https://www.tatachemicalseurope.com/about-us/carbon-capture-utilisation (Accessed: April 22, 2022).

The Energy Research Partnership (2021) The Environmental Constrains of Net-Zero. Available at: https://erpuk.org/project/the-environmental-constrains-of-net-zero/ (Accessed: April 21, 2022).

TIFAC (2018) *Carbon Capture Utilization & Storage: A Roadmap for India*. New Delhi.

TNN (2020) Coal India floats global tender for methanol plant at Dankuni, The Times of India. Available at: https://timesofindia.indiatimes.com/business/india-business/coal-india-floats-global-tender-for-methanol-plant-at-dankuni/articleshow/78374525.cms (Accessed: April 3, 2022).

Traverse (2021) Carbon Capture Usage and Storage Public Dialogue. Available at: www.traverse.ltd.

Turrell, W.R. et al. (2022) "A Review of National Monitoring Requirements to Support Offshore Carbon Capture and Storage," Frontiers in Marine Science, 0, p. 196. doi:10.3389/FMARS.2022.838309.

TWI Carbon Capture, Utilisation and Storage: Why Does It Matter? - TWI. Available at: https://www.twi-global.com/media-and-events/press-releases/2021/carbon-capture-utilisation-and-storage-why-does-it-matter (Accessed: April 22, 2022).

UKCCSRC (no date a) About Us - UKCCSRC. Available at: https://ukccsrc.ac.uk/about-us-ukccsrc/ (Accessed: April 22, 2022).

UKCCSRC (no date b) Core Research Projects: Systems & Policy, CB1 - Social license to operate - UKCCSRC. Available at: https://ukccsrc.ac.uk/research/core-research-projects/cb1-social-license-to-operate/ (Accessed: April 22, 2022).

UKCCSRC (2022) UKCCSRC Workshops. Available at: https://ukccsrc.ac.uk/ukccsrc-workshops/ (Accessed: April 22, 2022).

University of Sheffield Carbon capture equipment – TERC. Available at: https://terc.ac.uk/equipment/carbon-capture-equipment/ (Accessed: April 22, 2022).

Vishal, V. et al. (2018) "Simulation of CO2 enhanced coalbed methane recovery in Jharia coalfields, India," Energy, 159, pp. 1185–1194. doi:10.1016/J.ENERGY.2018.06.104.

Vishal, V., Chandra, D., et al. (2021) "Understanding initial opportunities and key challenges for CCUS deployment in India at scale," Resources, Conservation and Recycling, 175. doi:10.1016/j.resconrec.2021.105829.

Vishal, V., Verma, Y., et al. (2021) "A systematic capacity assessment and classification of geologic CO_2 storage systems in India," International Journal of Greenhouse Gas Control, 111. doi:10.1016/j.ijggc.2021.103458.

Yadav, A. et al. (2016) "Pilot project at Hazira, India, for capture of carbon dioxide and its biofixation using microalgae," Environmental Science and Pollution Research, 23(22), pp. 22284–22291. doi:10.1007/s11356-016-6479-6.

Zimmermann, A.W. et al. (2020) "Techno-Economic Assessment Guidelines for CO2 Utilisation," Frontiers in Energy Research, 8, p. 5. doi:10.3389/FENRG.2020.00005/BIBTEX.

10 Acknowledgements

The report is part of scoping exercise led by UKRI's NERC, ESRC, EPSRC and DST India and commissioned to Carbon Limiting Technologies (CLT) with the support of the Climate Collective Fund (CCF). The report is for UKRI and DST, funded by UKRI India.

UK Research and Innovation (UKRI) launched in April 2018. UKRI is a non-departmental public body sponsored by the Department for Business, Energy and Industrial Strategy (BEIS). The organisation brings together the seven disciplinary research councils, Research England, which is responsible for supporting research and knowledge exchange at higher education institutions in England, and the UK's innovation agency, Innovate UK. The nine councils work together in innovative ways to deliver an ambitious agenda, drawing on the great depth and breadth of expertise and the enormous diversity of the portfolio. www.ukri.org

UKRI India plays a key role in enhancing the research and innovation collaboration between the UK and India. Since 2008, the UK and Indian governments, and third parties, have together invested over £330 million in co-funded research and innovation programmes. This investment has brought about more than 258 individual projects. The projects were funded by over 15 funding agencies, bringing together more than 220 lead institutions from the UK and India. These research projects have generated more than £450 million in further funding, mainly from public bodies but also from non-profit organisations and commercial entities, attesting the relevance of these projects. www.ukri.org/india

The Department of Science and Technology (DST) plays a pivotal role in the promotion of science & technology in the country. The department has wide-ranging activities ranging from promoting high-end basic research and development of cutting-edge technologies, on one hand, to service the technological requirements of the common man through the development of appropriate skills and technologies on the other. Along with other mandates and responsibilities of DST, DST is continuously working on the identification and adoption of the right balance of the portfolio of emission curtailment technologies. Carbon Capture, Utilization, and Storage (CCUS) are among such key pathways to reduce emissions while continuing to develop sustainably at an unprecedented pace. CCUS clearly aligns with five of the seventeen Sustainable Development Goals (SDGs), namely, climate action; clean energy; industry, innovation, and infrastructure; responsible consumption and production; and partnerships to achieve the goals. https://dst.gov.in/

Carbon Limiting Technologies (CLT) is an established consultancy specialising in the commercialisation and deployment of sustainable technologies in energy, industry, transport, built environment & waste sectors to enable rapid decarbonisation. CLT has extensive knowledge and experience of the UK and international CCUS landscape, drawing on the experience of its network of 25 associates, each with more than 15 years

of experience in their field. Across both the public and private sectors, CLT has designed and delivered programmes which support decarbonisation through innovation including CCUS, energy efficiency and, the incorporation of newly developed technologies. CLT has also supported the development of low carbon policy internationally for innovation, finance and deployment of technologies. https://www.carbonlimitingtechnologies.com/

Climate Collective Fund (CCF) is, by far, the largest climate and cleantech start-up support organization in India, with over 610+ cleantech start-ups in our accelerators since 2018. These have included CCUS companies within its programmes. CFF has experience in developing sector road maps and working closely with a range of stakeholders to develop clear and precise overviews of technology sectors. The stakeholders often include academia and government as partners. https://climatecollective.net/

Glossary

Acronym	Full Form
APBS	Amine-Promoted Buffer Salts
ACT	Accelerating CCS Technologies
BECCS	Bioenergy with Carbon Capture and Storage
BEIS	Department for Business, Energy and Industrial Strategy
BGS	British Geological Survey
BHEL	Bharat Heavy Electricals Limited
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CCSA	Carbon Capture and Storage Association
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CDCL	Coal Direct Chemical Looping
CEEW	Council on Energy, Environment and Water
COF	Covalent Organic Frameworks
COMICS	Containment risk Mitigation in Indian CO_2 Storage
CSIR	Central Salt & Marine Chemicals Research Institute
DAC	Direct Air Capture
DfE	Department for Education
DME	Dimethyl Ether
DST	Department of Science & Technology
DBT	Department of Bio-Tchnology
ECBMR	Enhanced Coal Bed Methane Recovery
EGR	Enhanced Gas Recovery
EOR	Enhanced Oil Recovery
EPSRC	Engineering and Physical Sciences Research Council
ESRC	Economic and Social Research Council
ETI	Energy Technologies Institute
EU	European Union
FBC	Fluidised Bed Combustion
GERC	GeoEnergy Research Centre

GGR	Greenhouse Gas Removal
GHG	Green House Gas
ICOSAR	The Indian CO_2 Sequestration Applied Research
IEA	International Energy Agency
IFFCO	Indian Farmers Fertiliser Co-Operative
IGCC	Integrated Gasification Combined Cycle
IICT	Indian Institute of Chemical Technology
IISER	Indian Institutes of Science Education and Research
IIT	Indian Institute of Technology
INDC	Intended Nationally Determined Contribution
IOCL	Indian Oil Corporation Limited
IPHE	International Partnership for a Hydrogen Economy
IRENA	International Renewable Energy Agency
JNCASR	Jawaharlal Nehru Centre for Advanced Scientific Research
LCA	Life-Cycle Analysis
MHI	Mitsubishi Heavy Industries
MIT	Marathwada Institute of Technology
MoC	Ministry of Coal
MoEFCC	Ministry of Environment, Forest and Climate Change
MoF	Ministry of Finance
MOF	Metal Organic Frameworks
MoP	Ministry of Power
MoPNG	Ministry of Petroleum and Natural Gas
MTR	Membrane Technology and Research
NALCO	National Aluminium Company Limited
NAPCC	National Action Plan on Climate Change
NC-CCU	National Centre in Carbon Capture and Utilisation
NCoE-CCU	National Centre of Excellence in Carbon Capture and Utilisation
NERC	Natural Environment Research Council
NETRA	NTPC Energy Technology Research Alliance
NGRI	National Geophysical Research Institute
NIT	National Institute of Technology

NPL	National Physical Laboratory
NTPC	National Thermal Power Corporation Limited
NZIP	Net Zero Innovation Portfolio
O&G	Oil & Gas
OIL	Oil India Limited
ONGC	Oil and Natural Gas Corporation
PACT	Pilot Advanced Capture Technology Facilities
PSA	Pressure Swing Adsorption
PSU	Public Sector Undertakings
R&D	Research & Development
RGPV	Rajiv Gandhi Proudyogiki Vishwavidyalaya
SCCS	Scottish Carbon Capture & Storage
SHS	Subsurface H_2 Storage
SME	Small and Medium Enterprises
TDB	Technology Development Board
TEA	Techno-Economic Analysis
TERC	Translational Energy Research Centre
TERI	The Energy & Resources Institute
TIFAC	Technology Information forecasting & Assessment Council
TRL	Technology Readiness Level
TSA	Temperature Swing adsorption
TWI	The Welding Institute
UCL	University College London
UK	United Kingdom
UKCCSRC	UK Carbon Capture and Storage Research Centre
UK ETS	UK Emissions Trading Scheme
UKRI	UK Research and Innovation
UNFCCC	United Nations Framework Convention on Climate Change

Appendix

11.1 UK Data

11.2 India Data

1.1 Universities

				Research Focuses						
#	**University Name**	**Campus location(s)**	**Description of CCUS capability**	**Capture**	**Utilisation**	**Transport**	**Storage**	**TRL**	**Website**	**Search terms and Source of data**
1	University of Sheffield	Sheffield	Translational Energy Research Centre (TERC) at the university of Sheffield is home to Pilot Advanced Capture Technology Facilities (PACT). This is the UK's Leading CCUS research facility. This includes a 1t/day amine solvent based capture facility, with tuneable flue gas input and a rotating packed bed . Research includes BECCS and CCUS	x	x			1-4	https://terc.ac.uk/	UK CCUS Demonstrator https://terc.ac.uk/equipment/carbon-capture-equipment/ University of Sheffield PACT
2	Swansea University	Swansea	Leading the Reducing Industrial carbon Emissions (RICE) Programme, via its Energy Safety Research Institute. Focus on both capture and valorisation of CO2 through new routes to products from CO2	x	x			1-4	http://www.esri-swansea.org/en/carbon-dioxide.htm	Swansea University CCUS ESRI Swansea
3	Imperial College London	London	Has the UK's largest research programme, and have a newly refurbished CO2 pilot plant. Also host the Qatar Storage research centre. It also has the Grantham institute which has wider Climate change research including social impacts, and the Energy Futures Lab which includes policy research	x	x		x	1-6	https://www.imperial.ac.uk/carbon-capture-and-storage/ http://www.imperial.ac.uk/chemical-engineering/discovery/facilities/	Imperial College CCUS
4	Nottingham University	Nottingham	Nottingham has a CCUS Research lab including a facility which is able to test new sorbents on at 5-20kg scale. They have also carried out research to better understand storage conditions and behaviours	x			x	1-4	https://www.nottingham.ac.uk/carbonmanagement/	Nottingham CCUS facilities
5	Manchester University	Manchester	Focus on Subsurface Energy through the Manchester Environmental Research Institute (MERI), particularly storage and transport, And the impact and LCA/Social factors through the Tyndall Centre			x	x	1-4	https://www.meri.manchester.ac.uk/research/expertise/subsurface-energy/ https://www.tyndall.manchester.ac.uk/	Manchester University CCUS
6	Cranfield University	Cranfield	Cranfield has a wide range of CCUS facilities using a wide range of technologies. This includes the technologies to measure the composition of flue gases, the ability to trial new technologies on live-like flues and CO2 transport flow rigs. Facilities range from 60kWth - 750kWth plants. Technologies include Membrane, Chemical Looping, Solid Sorbent	x	x	x		1-7	https://www.cranfield.ac.uk/academic-disciplines/carbon-capture-and-transport https://www.cranfield.ac.uk/facilities/energy-technology-laboratory	https://www.cranfield.ac.uk/academic-disciplines/carbon-capture-and-transport Cranfield CCUS
7	Cardiff	Cardiff	Projects to research the capture properties of different Flue Gas mixtures, from both power and industry. These are based on a range of combustion facilities, including the UK gas turbine facility. Led by Centre for Research into Energy, Waste and the Environment	x				1-4	https://www.cardiff.ac.uk/research/explore/research-units/centre-for-energy-waste-and-the-environment	Cardiff University CCUS
8	Strathclyde	Glasgow	Strathclyde have significant research into CCUS through a range of engineering departments and humanities departments. Much of this is built on existing sub surface technology	x			x	1-4	https://www.strath.ac.uk/engineering/aboutus/carboncapturestorage/	University of Strathclyde CCUS
9	UCL	London	Primarily social impact of CCUS and modelling its impact on UK energy systems	x				1-4	https://www.ucl.ac.uk/bartlett/sustainable/research-projects/2021/sep/uk-	UCL CCUS research

10	University of Greenwich	London	Capture and Utilisation, including spin out Carbon8	x	x			1-7	https://www.gre.ac.uk/articles/greenwich-research-and-enterprise/research-case-study-prof-colin-hills-carbon8-systems-development-and-commercialisation-of-accelerated-carbonation-technology-act-to-produce-carbon-negative-aggregates-for-the-construction-industry	UKCCSRC members
11	University of Edinburgh	Edinburgh	Primarily looking at capture through absorption and membrane technologies. They have a new lab designed for testing these types of materials	x				1-4	https://carboncapture.eng.ed.ac.uk/projects	SCCS Centre
12	University of Cambridge	Cambridge	Significant CCUS research across a range of faculties, in both UK and Singapore - This includes capture and utilisation, but all at lab scale	x	x	x		1-4	https://www.energy.cam.ac.uk/directory/research-themes/supply/carbon-capture-storage-and-use	Cambridge CCUS Research
13	Durham University	Durham	Research into UK CCUS storage through the Earth Science department and the Energy Institute				x	1-5	https://www.durham.ac.uk/research/institutes-and-centres/durham-energy-institute/	Durham university CCUS
14	Newcastle University	Newcastle upon Tyne	Research into CCUS through the Engineering department, particularly Capture and Utilisation. They have worked with carbon clean	x	x			1-7	https://www.ncl.ac.uk/engineering/research/	Newcastle University CCUS
15	University of Southampton	Southampton	Viridi CO2 has spun out of the Chemistry department, focusing on utilisation. Also has focus on wider capture and storage	x	x			1-4	https://www.southampton.ac.uk/cleancarbon/research/homepage-capture.page	Southampton University CCUS
16	University of Oxford	Oxford	Predominately a policy and economic angle focus, with less clear work on the technical aspect	x	x	x	x	1-4	https://www.oxfordenergy.org/energy-transition-research-initiative/carbon-research-themes/	University of oxford CCUS
17	London School of Economics	London	LSE hosts: The Centre for Climate Change Economics and Policy, Centre for Economic Performance, Grantham Institute on Climate Change and Environment, Programme on Innovation and Diffusion. These all carryout general climate research, including on CCUS	x	x	x	x	1-4	https://www.lse.ac.uk/granthaminstitute/publication/seizing-sustainable-growth-opportunities-from-carbon-capture-usage-and-storage-in-the-uk/	LSE CCUS, Also found via Social papers
18	University of Leeds	Leeds	Focus on capture technologies, C-Capture spun out from the department	x				1-5	https://eps.leeds.ac.uk/research-innovation/doc/research-groups	Found via collaboration with LSE
19	Heriot Watt University	Edinburgh	CCUS research and geoscience expertise	x	x		x	1-4	https://www.hw.ac.uk/uk/research/global/zero-carbon/carbon-capture.htm	SCCS Centre
20	University of Aberdeen	Aberdeen	Predominately storage and BECCS, based on existing pipeline and storage work. Part of SCCS	x		x	x	1-4	https://www.abdn.ac.uk/energy/projects/carbon-capture-and-natural-capital-280.php	SCCS Centre

1.2 R&D Institutes

#	Institute Name	Campus location(s)	Description of CCUS capability	Key CCUS research areas				TRL	Website	Search terms and Source of data
				Capture	Utilisation	Transport	Storage			
1	British Geological Survey	Nottingham, Edinburgh	British Geological survey is the UK geological survey and geoscience organisation. It has prepared a wide range of CO2 storage research as the leading data provider in the UK			x	x	N/A	https://www.co2stored.co.uk/home/about	UK CCUS facilities
2	Energy Technologies Institute	Closed	Looked at storage monitoring - CO2 leakage detection Survey of MMV tools/innovators			x	x		https://www.eti.co.uk/	Found Via UKCCSRC
3	GeoEnergy Research Centre (GERC)	Nottingham, BGS	Goal is to address the global energy trilemma of affordability, security and sustainability of energy supply. GERC will do this by focusing combined capabilities to enable the sustainable and cost-effective use of geoenergy resources. Undertake joint research into subsurface energy processes for a range of geoenergy sectors specifically; areas of fluid-rock interactions, sensor development and demonstration of monitoring technologies			x	x		http://www.gerc.ac.uk/geoenergyresearchcentre.aspx	Found through link from UKCCSRC
4	IEAGHG R&D programme	Cheltenham	IEA Green House Gas R&D programme is a Technology Collaboration Partner of the IEA, ensuring that there is significant sharing of information and supporting collaboration in research. It assesses the roles that technologies can play in reducing greenhouse gas emissions from power and industrial processes. IT produces reports by working with academic institutions and technical consultancies	x	x	x	x	N/A	https://ieaghg.org/	IEA GHG
5	National Oceanography Centre	Southampton	Working on understanding the hazards and issues in CO2 storage on oceans				x	1	https://noc.ac.uk/projects/stemm-ccs	UKCCSRC funding pages
6	NPL	Greater London	National Physical Laboratory focuses on measurement and standards, across the value chain	x	x	x	x		https://www.npl.co.uk/energy-transition/carbon-capture-usage-storage	NPL CCUS
7	Scottish CCS Centre	British Geological Survey, Heriot-Watt University, the University of Aberdeen, the University of Edinburgh, the University of Glasgow and the University of Strathclyde	SCCS is the largest CCS research group in the UK, providing a single point of coordination for CCS research, from capture engineering and geoscience to social perceptions and environmental impact through to law and petroleum economics	x	x	x	x	N/A	https://www.sccs.org.uk/about-us	SCCS
8	TWI Ltd	Cambridge	The Welding Institute' - private material science research organisation. Focusing on Materials for the highly acidic CCUS environments		x	x	x	N/A	https://www.twi-global.com/media-and-events/press-releases/2021/carbon-capture-utilisation-and-storage-why-does-it-matter	UK CCUS Material research
9	UK CCS RC	Sheffield, Cambridge, Imperial College, Nottingham, Manchester, Cranfield, Cardiff, Strathclyde, UCL	UK CCS research body, bringing together a wide range of academic institutions to coordinate research. Coordinate and run funding from EPRSC for all aspects of CCUS. Promotes UK CCUS research, including holding MoU's with CCUS organisations in 6 other countries (Australia, Canada, China, Netherlands, South Korea, USA). This is responsible for the deployment of PACT	x	x	x	x	1-9	https://ukccsrc.ac.uk/	UKCCSRC

1.3 SMEs

#	Company name	Main location(s)	Description of CCUS capability	Key CCUS activity areas: Capture	Utilisation	Transport	Storage	TRL	Website	Search terms and Source of data
1	Econic	Oxford	Catalysts for CO2 utilisation to convert it into plastics		x			4	https://econic-technologies.com/	Econic
2	Viridi CO2	Southampton	CO2 activation catalysts to support the initial steps in chemical pathways to high value products		x			4	https://www.viridico2.co.uk/	Viridi CO2
3	PMW Technologies	Chester	Cryogenic CO2 capture, primarily targeting shipping and industry	x				5	https://www.pmwtechnology.co.uk/	PMW Technologies
4	DeepBranch	Nottingham	CO2 utilisation growing microbes to produce protein. Running a trial with Drax		x			5	https://deepbranch.com/	DeepBranch
5	MOF Technologies	Belfast	Carbon capture using Metal Organic Frame works	x				5	https://www.moftechnologies.com/	MOF Technologies
6	Promethean Particles	Nottingham	Carbon capture using Metal Organic Frame works	x				5	https://prometheanparticles.co.uk/	Promethean Particles
7	Sphera	Durham	Produce a carbon negative aggregate for use in concrete blocks, capturing CO2 from flue gases		x		x	5	https://sphera.uk/products/	Sphera
8	Cambridge Carbon Capture	Cambridge	Capturing CO2 from waste flues to use in aggregates	x	x			5	https://www.cacaca.co.uk/	Cambridge CCUS
9	PolyCapture	Cambridge, Leicester	Polymer based capture material and system. Spun out of Cambridge and Cranfield	x				6	https://www.polycapture.co.uk/	PolyCapture
10	Carbon8	Nottingham	Carbonation of industrial residues from flue gas to form usable aggregates that can be used in concrete which stores the CO2	x	x		x	6	https://c8s.co.uk/	Carbon 8
11	CCM	Swindon	Carbon capture and utilisation technology, converting CO2 waste stream into fertilisers and plastics	x	x			6	http://ccmtechnologies.co.uk/	CCM
12	C-Capture	Leeds	Non Amine solvent base capture technology - now working with Drax as part of a bio gas trial, aiming for 10000t/day	x				7	https://www.c-capture.co.uk/	C-Capture
13	Origen	Oxford	Uses Lime based capture and slacking, focused purely on the cement and lime industries. Currently working with Singleton Birch to develop the tech, also demonstrating at Tate and Lyle	x				7	https://origencarbonsolutions.com/	Origen
14	OCO Technologies	Suffolk	Create aggregates from fuel waste using accelerated Carbonation to create the solids, which can then be used in building materials	x	x		x	8	https://oco.co.uk/	Accelerated Carbonisation UK
15	Carbon Clean	London, Mumbai, Chicago, Alicante, Hamburg	Developed a proprietary amine solvent for CO2 capture (CDR MAX). They have achieved up to 150t/day capture. They are involved in the UK Acorn Cluster and 44 projects total word wide, including 2 in India	x	x			9	https://www.carbonclean.com	Carbon Clean
16	Progressive Energy	Gloucester, Liverpool	Project developer of renewable energy projects, including leading the consortium for the HyNet Cluster					N/A	https://www.progressive-energy.com/	Progressive Energy

1.4 Large Enterprises

#	Company name	Main location(s)	Description of CCUS capability	Key CCUS activity areas: Capture	Utilisation	Transport	Storage	TRL	Website	Search terms and Source of data
1	Aker	Aberdeen	Engineering firm focused on Carbon Capture explicitly. Built on amine technology	x	x			7	https://www.akersolutions.com/who-we-are/	Planned EfW
2	bp	Norther Endurance Partnership	Lead operator of the Northern endurance partnership and responsible for some of the storage and transport aspects of this	x		x	x	9	https://www.bp.com/en/global/corporate/news-and-insights/reimagining-energy/northern-endurance-partnership-to-develop-offshore-ccus-infrastructure.html	Northern Endurance partnership
3	Drax	Selby, North Yorkshire	Drax have two pilot facilities at Drax Power Station which is fired by biomass. The first utilises C-Capture's Technology (University of Leeds Spin out) which is aiming to capture 1t/day. This launched in 2019 and is still operational. The second pilot at the plant uses Mitsubishi's KS-1 (proven) and KS -21 Solvents (novel) and will capture 300kg/day. This pilot launched in 2020	x				8-9	https://www.drax.com/about-us/our-projects/bioenergy-carbon-capture-use-and-storage-beccs/	Drax BECCS https://co2re.co/
4	ENI	Part of the HyNet Cluster	Responsible for the transport and storage of CO2 from the HyNet Project			x	x	7	https://www.eni.com/en-IT/media/press-release/2021/05/eni-and-progressive-energy-join-forces-to-accelerate-uk-ccs-development.html	ENI CCUS UK
5	Equinor	Norther Endurance Partnership	Equinor are supporting the storage aspects of the East coast cluster through this programme, including being on the join licences for the storage			x	x	9	https://www.equinor.com/en/where-we-are/united-kingdom/Northern-Endurance-Partnership-NEP.html	Northern Endurance partnership
6	Johnson Matthey	London	Primarily focused on Blue hydrogen Capture, from reforming, can achieve 95%+ capture	x				8	https://matthey.com/en/news/2020/jms-leading-low-carbon-hydrogen-technology-scoops-icheme-award	Johnson Matthey CCUS
7	kellas	East Coast Cluster	Kellas are a major natural gas distribution company, owning and operating pipelines, now looking to enter the CO2 market			x		9	https://www.kellasmidstream.com/news-kellas/hydrogen-production-in-teesside	Northern Endurance partnership
8	Mitsubishi	Selby, North Yorkshire	Demonstrating their Amine Solvent CCUS at the Drax site	x				7	https://www.mhi.com/news/210610.html	Mitsubishi CCUS
9	National Grid	East coast cluster	Developing the onshore pipelines for the clusters due to existing pipeline know how			x			https://www.nationalgrid.com/our-businesses/national-grid-ventures/humber-low-carbon-pipelines	National Grid CCUS
10	Shell	Acorn, East Coast Cluster, SWIC	Taking part in 3 of the UK clusters, as well as developing their own amine solvent (CanSolv) which they have deployed at a plant in the US. Also involved in a major storage trial (Northern Lights) in Norway	x		x	x	9	https://www.shell.co.uk/a-cleaner-energy-future/carbon-capture-and-storage.html	Shell CCUS
11	Tata Chemicals	Northwich	Have installed CO2 capture technology on a n Combined heat and power plant at their Northwich facility, are using the CO2 in the production of Sodium Bicarbonate	x	x			9	https://www.tatachemicalseurope.com/about-us/carbon-capture-utilisation	Tata Chemicals CCUS
13	Total Energies	Northern Endurance Partnership	Part of the consortium, providing some technical support to the development of the network. Also building on lessons learned from the Northern lights project			x	x	9	https://ep.totalenergies.com/en/joining-forces-you/carbon-neutrality/totalenergies-invests-heavily-carbon-capture-utilization-and	Northern Endurance partnership

1.5 Projects

#	Project name	Main location(s)	Leading participants	Description of project	Capture	Utilisation	Transport & Storage	Project status	Year	Final Investment Decision date (if known)	Website	Search terms and Source of data
1	HyNet	Liverpool	Progressive Energy Ltd (lead) Cadent Gas Ltd University of Chester CF Fertilisers UK Ltd ENI UK Ltd Essar (UK) Ltd Johnson Matthey Castle Cement Ltd Inovyn Enterprises Ltd. Hanson InterGen Encirc, Pilkington, Unilever, Viridor, ingevity, Cargill, Ibstock, Heineken, Peel L&P, essity, Solvay, Kellogg's, Uni Per, JLR, Glass Futures, Tata Chemicals, PepsiCo, Kraft	One of the Track one selected clusters designed to come online in 2025. From 2025, HyNet is aiming to produce blue hydrogen in the Northwest of England, as well as capturing CO2 from industry in the region. The CO2 will then be transported and stored in the region. Capturing Up to 10 Mt/y by 2030	x	x	x	Development	Ongoing	2022/23	https://hynet.co.uk/	HyNet
2	East Coast Cluster	Teesside, Humberside	Lead Partners: BP, ENI, Equinor, National Grid, Shell, Total Energies Project Partners: 8Rivers, BOC, CF Fertiliser, Drax, H2Teesside, kellas, Mitsubishi power, SSE Thermal, Suez, triton power, uni per, Velocys	A combination of Net Zero Teesside, ZeroCarbon Humber, (Two Net zero industrial clusters) and Norther endurance, a storage location in the north sea). This is the second track one cluster for UK CCUS Capturing ip to 27 Mt/y by 2030	x	x	x	Development	Ongoing - operational by 2025	2022/23	https://eastcoastcluster.co.uk/	East Coast Cluster, UK Government Cluster Announcements
3	Acorn	Grangemouth, Aberdeenshire	Storegga, Shell, Harbour Energy, North Sea Midstream Partners	Selected as the reserve for Track Clusters for the UK, and likely to be selected in track 2. This is based in Grangemouth and will focus on collection from a refinery and natural gas site Capturing 5-10 Mt/t (by 2030)	x	x	x	Development	aiming for 2025 decision	2025<	https://theacornproject.uk/	Acorn Cluster
4	South Wales Industrial Cluster (SWIC)	South Wales	Lead: Costain Associated British Ports, Capital Law, CR Plus, Industry Wales, Lanzatech, Lightsource bp, Milford Haven Port Authority, Progressive Energy, RWE Generation, Shell, Simec Power, Tarmac, Tata Steel, The Port of Milford Haven, The University of South Wales, Valero Energy and Wales & West Utilities	Cluster targeting decarbonising the south coast of Wales, focusing on the heavy industry there. Faces a major challenge because there is no storage directly adjacent to the location Capturing 16 Mt/y	x	x		Development	2025<	2025<	https://www.swic.cymru/	SWIC, UK Clusters
5	Tata Chemicals	Northwich	Tata Chemicals, Pent Air Union	Tata Chemicals installed a Pentair-Union CC technology on their on site CHP plant, and are using the captured CO2 for manufacture of the Sodium bicarbonate Capturing 40 kt/y currently				Operation	2021	2019	https://www.tatachemicalseurope.com/about-us/carbon-capture-utilisation#First_Industrial_Scale_Carbon_Capture	Tata CCUS plant

1.6 Technologies

#	Technology Type	Technology name	Leading participants	Description of technology	TRL	Website	Search terms and Source of data
1	**Carbon Capture**	MOF (Metal-Organic Frameworks)	MOF Technologies	Super-adsorbent materials engineered to improve gas-separation process. They can be designed to specifically capture CO2, and when combined with VPSA (Vacuum Pressure Swing Adsorption) system can cut energy consumption in up to 80% when compared to amine-based systems	4	https://www.moftechnologies.com/mofs-for-co2	MOF Technologies
2	**Carbon Capture**	Cryogenic	PMW Technologies	CO2 is frozen out of a waste stream, and the solid CO2 collected. Requires significant energy to cool CO2	4	https://www.sciencedirect.com/science/article/abs/pii/S0360544212006184	
3	**Carbon Capture**	Polymer Adsorbent	PolyCapture	CO2 is captured via adsorption onto a polymer surface via physical and chemical adsorption	6	https://www.polycapture.co.uk/	
4	**Carbon Capture**	Oxy-Fuel	8rivers/NetPower	Carbon Containing fuel is burned in a CO2 atmosphere with almost pure CO2, within exact quantity of pure oxygen. CO2 can then be removed from the system, along with some water	6	https://www.sciencedirect.com/science/article/abs/pii/S0360544212006184	
5	**Carbon Capture**	Advanced Amine	Mitsubishi	New amines, which are a development on the existing technologies, either with lower energy to	7	https://www.mhi.com/products/engineering/co2plants.html	
6	**Carbon Capture**	Non-ammine solvents	Carbon Clean	Solvents not based on amine solvation of CO2, these are just beginning to be developed	7	https://www.carbonclean.com/solvents	
7	**Carbon Capture**	Metal carbonate solids	Origen	This uses a process where alkaline metal carbonates are precipitated out of a solution based containing the metal ions. The carbonate is then heated to drive off the CO2, for Capture	7		
8	**Carbon Capture**	Direct Air Capture (DAC)	Storegga, Carbon Engineering	Direct air capture (DAC) technologies extract CO2 directly from the atmosphere. The CO2 can be permanently stored in deep geological formations	7	https://www.nature.com/articles/s41467-019-10842-5	
9	**Carbon Capture**	Traditional Amine Solvent	Shell, Fluor, Aker Solutions	Passes flue class through a solution containing an amine solvent. Most common way to adsorb CO2 from gaseous streams. High energy required to heat water during CO2 recovery step	9	https://ukccsrc.ac.uk/wp-content/uploads/2021/06/BAT-for-PCC_V1_0.pdf	
10	**Carbon Capture**	Polymeric Membranes	MTR	A mature technology, where CO2 is separated using a selective membrane. Requires a very large surface area	9	https://www.sciencedirect.com/science/article/abs/pii/S0360544212006184	
11	**Carbon Utilisation**	Biological Conversion of CO2	DeepBranch	CO2 can be converted to other products (e.g. carboxylic acids, proteins, alcohols, fatty acids) using microorganisms (e.g. yeasts, bacteria) in gas fermentation or through the use of algae-based systems	1	https://www.iea.org/reports/putting-co2-to-use	
12	**Carbon Utilisation**	Chemical conversion to chemicals and fuels	Econic, Viridi CO2, CCM Technologies	CO2 is usually reacted with hydrogen. Key chemical intermediates are produced (e.g. methanol, methane) that can be then converted to wide range of chemicals, including gasoline and aviation fuels (via Fischer-Tropsch route), olefins (via methanol-to-olefins route) as well as plastics. CO2 can also be used in urea production	4	https://www.iea.org/reports/putting-co2-to-use https://www.ingentaconnect.com/content/matthey/jmtr/2021/00000065/00000002/art00003;jsessionid=7a0hpp99sd9rb.x-ic-live-02#	CO2 Utilisation

13	**Carbon Utilisation**	Mineral carbonation	Carbon 8	CO2 is captured through accelerated reactions with certain rocks, storing the CO2 in a mineral form. This can also be used to produce aggregates	7	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/799293/SISUK17099AssessingCO2_utilisationUK_ReportFinal_260517v2__1_.pdf	
14	**Carbon Utilisation**	Enhanced oil recovery (EOR)	BP, Shell	CO2 is injected in injection wells, penetrating into the rocks pores and flushing residual oil into the production wells	8	https://www.ogauthority.co.uk/exploration-production/development/enhanced-oil-recovery/	EOR Technologies
15	**Carbon Utilisation**	Direct CO2 utilisation	Tata Chemicals	CO2 can be directly used in several applications such as: direct solvent (for dry cleaning, decaffeination, enhanced oil recovery), heat transfer fluid (refrigeration, supercritical power systems, etc), in food and beverages production, medical systems, to improve yield in greenhouses or algae productions as well as in urea/fertiliser production	9	https://www.iea.org/reports/putting-co2-to-use	CO2 Utilisation
16	**Storage**	Storage in Saline formations	BP, Shell	Saline formations have a huge CO2 storing. CO2 dissolves into the saline solution and can further react with minerals present in the rocks, forming solid carbonate minerals	8	https://www.frontiersin.org/articles/10.3389/fclim.2019.00009/full	
17	**Storage**	Depleted oils and gas reservoirs	Eni UK	Depleted Oil and Gas reservoirs are used to storage CO2	8	https://www.ogauthority.co.uk/news-publications/news/2020/energy-integration-in-action-eni-project-awarded-carbon-storage-licence/	
18	**Transport**	Shipping	Praxair	The TRL for CO2 shipping ranges from 3 to 9. The lowest TRL-3 relates to offshore injection into a geological storage site from a ship. The TRL-9 rating refers to conventional onshore CO_2 injection from onshore facilities (which can be delivered to the injection site by ship)	3	https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf	
19	**Transport**	Rail		CO2 is also transported by truck and rail. Fundamentally, the transportation of gases and liquids via any of these methods is mature (i.e. TRL 9). However, transportation of CO2 at the very large scale associated with CCS has not yet been achieved using ships or rail	7	https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf	
20	**Transport**	Pipeline	TWI	Only pipelines are transporting CO2 at significant scale	8	https://www.globalccsinstitute.com/wp-	
21	**Transport**	Truck		CO2 is also transported by truck and rail. Fundamentally, the transportation of gases and liquids via any of these methods is mature (i.e. TRL 9). However, transportation of CO2 at the very large scale associated with CCS has not yet been achieved using ships or rail	8	https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf	

1.7 Policy and Regulation

#	Policy or regulatory instrument name	Owning/administering organisation name	Description of policy or regulatory instrument	Year	Website	Search terms and Source of data
1	Indian Petroleum Act, 1934:	Government of India	Rules for production and transportation of petroleum products. It can be applied for transportation of compressed CO2	1934	https://legislative.gov.in/sites/default/files/A1934-30_0.pdf	Oil and Gas policies for carbon
2	The Petroleum Mineral Pipelines (Acquisition of Right of User in Land) Act, 1962	Government of India	Provides for the acquisition of user in land for laying pipelines for the transport of petroleum and minerals and for matters connected therewith. This law may be applied for transportation of compressed CO2 to storage sites	1962	https://legislative.gov.in/sites/default/files/A1962-50_0.pdf	Policies of carbon in India
3	National Statement by Prime Minister Shri Narendra Modi at COP26 Summit in Glasgow	Government of India	At the 26th Conference of Parties (CoP26), Indian Prime Minister Narendra Modi declared a five-fold strategy — termed as the panchamrita — to achieve this feat. These five points include: - India will get its non-fossil energy capacity to 500 GW by 2030 - India will meet 50 % of its energy requirements from renewable energy by 2030 - India will reduce the total projected carbon emissions by one billion tonnes from now onwards till 2030 - By 2030, India will reduce the carbon intensity of its economy by less than 45 % So, by the year 2070, India will achieve the target of Net Zero	2021	https://pib.gov.in/PressReleseDetail.aspx?PRID=1768712	
4	National Action Plan on Climate Change (NAPCC)	Ministry of Environment, Forest and Climate Change	The plan outlines a national strategy that aims to enable the country to adapt to climate change and enhance the ecological sustainability of India's development path. It stresses that maintaining a high growth rate is essential for increasing living standards of the vast majority of people of India and reducing their vulnerability to the impacts of climate change. Notable points on carbon: - National Mission for Green India: Greening is meant to enhance ecosystem services such as carbon sequestration and storage (in forests and other ecosystems) Enhancing carbon sinks in sustainably managed forests and other ecosystems	2008	https://static.pib.gov.in/WriteReadData/specificdocs/documents/2021/dec/doc202112101.pdf	Indian Strategy on Carbon capture, storage and utilization , Environmental policy on CCUS
5	Policy Framework to Promote and Incentivize Enhanced Recovery Methods for Oil and Gas	Ministry of Petroleum & Natural Gas	The policy will apply to all oil and gas fields across all contractual regimes and nomination acreages with National Oil Companies 10 year policy to screen fields for Enhanced Recovery	2018	http://petroleum.nic.in/sites/default/files/policyeng.pdf	Policy for EOR in India

6	Accelerating CCS Technologies	Multiple countries including India and UK	ACT is an international initiative to establish CO2 capture, utilisation and storage (CCUS) as a tool to combat global warming. ACT means Accelerating CCS Technologies, and the ambition of the 16 partners is to fund research and innovation projects that can lead to safe and cost-effective CCUS technology. The first ACT Call for project proposals was published in 2016 and resulted in eight projects that were started autumn 2017. The second ACT Call was published 2018. The budget for the call was € 31 M and 12 new projects started autumn 2019. The third ACT Call was published in 2020. The budget for the call is € 27M and 12 new projects are planned to commence in autumn 2021	2018	http://www.act-ccs.eu/	Policies for CCUS in India
7	Third Biennial Update Report to The United Nations Framework Convention on Climate Change	Ministry of Environment, Forest and Climate Change	The report embodies information on national circumstances, national GHG inventory, mitigation actions, and an analysis of the constraints, gaps, and related finance, technology and capacity building needs, including information on domestic measurement, reporting and verification (MRV) which includes the status of CCUS in India	2021	https://unfccc.int/sites/default/files/resource/INDIA_%20BUR-3_20.02.2021_High.pdf	Biennial update india, CCUS
8	Mission Innovation IC3	Lead: UK Participant: India	Launched in 2018 Mission Innovation will need to identify what can be done differently to accelerate CCUS. Technologies will need to be developed, tested, and vetted in collaborative forums, building on past experiences and improving on current efforts to further reduce costs.	2018	http://mission-innovation.net/our-work/innovation-challenges/carbon-capture/	CCUS policy and advocacy in India
9	India to have two National Centres of Excellence in Carbon Capture & Utilization at IIT Bombay & JNCASR, Bengaluru, supported by DST	PIB, DST	Two National Centres of Excellence in Carbon Capture and Utilization are being established in India. The two Centres, namely the National Centre of Excellence in Carbon Capture and Utilization (NCoE-CCU) at Indian Institute of Technology (IIT) Bombay, Mumbai and the National Centre in Carbon Capture and Utilization (NCCCU) at Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR), Bengaluru are being set up with support from the Department of Science & Technology, Govt. of India	2022	https://pib.gov.in/PressReleasePage.aspx?PRID=1797178	national strategy on CCUS India

1.8 TEA and LCA

#	Title of leading TEA and LCA CCUS publications	Lead author	Year	Summary of abstract	Weblink to document	Search terms and Source of data
1	Cost implications of Carbon Capture and Storage for the Coal Power Plants in India	Anand B. Rao, Piyush Kumar	2014	CCS is the process of extraction of CO2 from industrial and energy related sources, transport to storage locations and long-term isolation from the atmosphere. It is being considered as a bridging technology, with significant carbon mitigation potential, especially for large point sources such as coal power plants. it would be worthwhile to investigate the necessary and sufficient conditions under which the Indian power plants could graduate to the CCS technologies	https://www.sciencedirect.com/science/article/pii/S187661021401162X#:~:text=The%20values%20of%20incremental%20COE,rate%20of%20the%20base%20plant.	Cost analysis of CCUS in India
2	Techno-economic analysis of Carbon Mitigation Options for Existing Coal-fired Power Plants in India	Udayan Singh, Anand B Rao	2016	India's developmental needs in the near and long-term future will be strongly interlinked with the need to provide steady electricity to its cities and villages. The current fleet of Electricity Generating Units (EGUs) in India is mostly coal-based. There is a strong incentive for repowering of old plants to supercritical units and their subsequent retrofitting with CO2 capture systems than direct retrofitting of low performance plants	https://www.researchgate.net/publication/311483991_Techno-Economic_Assessment_of_Carbon_Mitigation_Options_for_Existing_Coal-fired_Power_Plants_in_India	techno economic study of Carbon capture , TEA on CCUS in India , carbon mitigation, cost of electricity in India
3	An improved tri-reforming based methanol production process for enhanced CO2 valorisation	Abhishek Dwivedi, Ravindra Gudi, Pratim Biswas	2017	The main contributions of this paper to the tri-reforming coupled methanol production process are: (i) proposition of a high pressure tri-reforming step to limit capital costs of the process (ii) establishment of steam input coupled with water separation step as a process improvement whose impact is shown to further amplify at higher tri-reformer pressures. The paper evaluates the process in terms of the profit generating and CO2 valorisation potential of the process as reflected by two parameters, gross margin (GM) and NPCV (net percentage of CO2 valorised) respectively	https://www.sciencedirect.com/science/article/abs/pii/S0360319917330021	CO2 valorization, Methanol production
4	Economic Implications of CO2 Capture from the Existing as well as proposed coal-fired power plants in India under various policy scenarios	Udayan Singh, Anand B Rao, Munish K. Chandel	2017	The paper assesses the economic implications of this technology on existing Indian coal-fired power plants. Some characteristic features of Indian power plants are identified with special reference towards CCS deployment	https://www.sciencedirect.com/science/article/pii/S1876610217320994	Carbon mitigation, clean coal technology, Economic implications of CCUS
5	Relevance of Carbon Capture & Sequestration in India's Energy Mix to achieve the reduction in emission intensity by 2030 as per INDCs	A.R. Akash, Anand B. Rao, Munish K. Chandel	2017	The main objective of this work is to understand the potential role of Carbon Capture & Sequestration (CCS) in coal based power sources in order to meet the committed reduction in the emission intensity (INDC) by the year 2030. The analysis has been carried out under several scenarios characterized by assumptions regarding the GDP growth rate, the energy mix and carbon price. The results indicate that India can meet the INDC by 2030 without deploying CCS in the coal power plants under most of the scenarios	https://www.sciencedirect.com/science/article/pii/S1876610217320854	Emissions, INDC, power and CCUS, carbon sequestration
6	Carbon capture and sequestration potential in India: A comprehensive review	Abhishek Gupta	2018	India's current and expected future emissions are sufficiently massive to have an adverse effect on global mitigation efforts. The IPCC studied that without CCS, the price of achieving long-run climate goals is almost 140% more expensive. However, India has been taking a cautious approach towards CCS technology due to various factors. The paper discusses on the challenges of CCS in India and a roadmap for the successful implementation	https://www.researchgate.net/publication/331695105_Carbon_capture_and_sequestration_potential_in_India_A_comprehensive_review	CCUS in India, carbon emission in India, Carbon sequestration in India

7	Oxy-fuel combustion based enhancement of the tri-reforming coupled methanol production process for CO2 valorisation	Abhishek Dwivedi, Ravindra Gudi, Pratim Biswas	2018	The main contributions of this paper are therefore (i) the proposition of combining oxy-fuel combustion with the tri-reforming coupled methanol production process to mitigate the above drawback, and (ii) utilization of water electrolysis as a source of oxygen and an evaluation of the impact of the generated hydrogen on the CO2 valorisation potential of the process. These two propositions have been implemented as process improvements on the conventional tri-reforming coupled methanol process. The resultant processes have been simulated using Aspen Plus V8.4, optimized and compared in this paper to justify their efficacy	https://www.sciencedirect.com/science/article/abs/pii/S2212982017306224	Oxyfuel combustion in India, CO2 utilization
8	Techno-economic analysis of a 660 MWe supercritical coal power plant in India retrofitted with calcium looping (CaL) based CO2 capture system	Srinath Haran	2021	The publication covers: Technoeconomic study of calcium looping (CaL) retrofitted to Indian coal powerplant. Comparison of CaL for different fuels in calciner and with MEA and Oxycombustion. Lowest LCOE obtained for Indian high ash coal, net negative emissions for biomass. Net power output of CaL system 94 and 81% more as compared to MEA and Oxycombustion. For same net power output, performance of CaL better than MEA and Oxycombustion	https://www.sciencedirect.com/science/article/abs/pii/S1750583621002735	Indian Coal , Chemical looping technology in India , CCUS technology in India
9	Evaluation of Techno-Economic Viability of Carbon Capture Utilization and Storage (CCU&S) with Carbon Credits for Steel Plants	Arunava Maity	2021	The steel sector is actively pursuing the development and adoption of carbon-lean technologies, among which CCUS plays a key role. Since the sources of direct CO2 emissions in the iron and steel sector are very site-specific and dependent on the iron making process, CCU&S in the steel industry faces a greater challenge with respect to choice of technology, process efficiency, total cost incurred and scale up for industrial applications	http://www.dastur.com/CCUS.aspx	CCUS and steel industry, Carbon sequestration , technoeconomic feasibility of CCUS in India

1.9 Skills and Employment

#	Title of leading CCUS skills and employment publications	Lead author	Summary of abstract	Weblink to document	Search terms and Source of data
1	CCUS Supply Chains: a roadmap to maximise the UK's potential	BEIS	Published in May 2021 this roadmap sets out how government and industry in the UK can work together to harness the power of a strong, industrialised UK CCUS Supply Chain. It covers 4 key themes: Supply Chain Mapping, Capability development, Skills and innovation, and finance and trade	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/984308/ccus-supply-chains-roadmap.pdf	UK Skills for CCUS
2	A Carbon Capture, Utilisation, & Storage Network For Wales	Welsh Government, DNV	Published in March 2021, this report covers the potential for the development of different pathways for the incorporation of CCUS in Wales's Net Zero Route map. It includes a focus on the storage options for Wales, including export and domestic storage options. Contains a section focusing on the skills required to build this	https://gov.wales/sites/default/files/publications/2021-10/a-carbon-capture-utilisation-and-storage-network-for-wales-report.pdf	Wales CCUS
3	Seizing sustainable growth opportunities from carbon capture, usage and storage in the UK	Grantham Institute (Imperial), LSE, Centre for Climate Change Economics and Policy, Oxford	This report focuses on the skills and economic impacts of deploying CCUS, and identifies those areas where it will have the greatest impact The report aim stop identify areas of opportunity for a sector for which we know there is an unambiguous commitment by government to expansion	https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2021/09/Seizing-Sustainable-Growth-Opportunities-from-CCUS-in-the-UK_FULL-REPORT-1.pdf	UK CCUS Skills
4	Green Jobs Taskforce: Report to Government, Industry and the Skills sector	BEIS and DfE	Report assembling the evidence on the skills needed in the green economy and stablishing how the industry, government and a wide range of stakeholders should work to address the identified challenges and opportunities in order to meet the government ambition of 2 m green jobs in 2030	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1003570/gjtf-report.pdf	UK CCUS Skills
5	The net zero skills issue: Bridging the gap to a low carbon workforce	Energy Institute	Report based on more than 400 professional selected to represent different views across the UK energy system	Barometer 2021 | Energy Institute (EI)	Energy Barometer 2021
6	The North Sea Transition Deal	NSTA	Sector deal between government and the offshore oil and gas industry to work together to deliver the skills, innovation and new infrastructure required to align the sector with net-zero, including ambitious domestic supply chain targets	https://www.gov.uk/government/publications/north-sea-transition-deal	Skills North sea transition deal

7	Economic Analysis of UK CCUS	CCSA	Report published by the CCSA and written by international engineering consultancy Afry and Cambridge Econometrics on the economic impact of scaling up CCUS in the 2020s. The report explores the impacts of rolling out CCUS in the 2020s under the Government's Ten Point Plan scenario to capture 10 Mt of CO2 a year by 2030, before scaling up in the 2030s; and under the Climate Change Committee's (CCC) Balanced Net Zero Pathway in the Sixth Carbon Budget to capture 22 Mt of CO2 a year by 2030. Considering the CCC scenario, 10,000 new jobs could be created for UK heartlands	https://www.ccsassociation.org/wp-content/uploads/2021/07/Economic-Analysis-of-UK-CCUS-June-2021-executive-summary.pdf	CCUS
8	Trade Deals to create green jobs in the UK	UK Government	18 new trade and investment deals worth £9.7bn have been secured at the Global in 2021 and will support green growth and create an estimated 30,000 UK jobs	https://www.gov.uk/government/news/investors-pledge-almost-10bn-at-uk-global-investment-summit	Gren Jobs
9	Skills and training for the green economy	CBI	Report submitted to the Green Jobs Taskforce, developed in partnership with business, trade bodies and education providers focused on three industries with most immediate targets for net-zero: home efficiency, automotive and clean power. The paper analyses the current skill gaps and makes recommendation on how the government can approach them, highlighting the importance the developing areas such as Hydrogen and CCUS in generating new jobs as well as providing new employment for declining areas of the energy sector. It also outlines mechanisms to develop the necessary skills and major recommendations for the government to incentivize it	https://www.cbi.org.uk/media/6525/skills-and-training-for-the-green-economy.pdf	Skills Green Jobs
10	The National Skills Fund: Government consultation response	Department for Education	The National Skills Fund consultation collected stakeholders' views on three primary areas, which the Government has responded to in turn. This document provides a high-level overview on the key feedback which came through in responses and how we have responded to this feedback.	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1065705/National_Skills_Fund_consultation_response.pdf	National skills Fund

1.10 Social Impacts

#	Title of leading social impacts of CCUS publications	Lead author	Summary of abstract	Weblink to document	Search terms and Source of data
1	Carbon capture usage and storage: public dialogue	BEIS/Traverse	UK gov report of 132 pages in detail on the topic published in August 2021. This was then evaluated in a 89 page review by Ursus consulting "Research into citizens' attitudes towards Carbon Capture Usage and Storage (CCUS), including views on: - future use of CCUS technologies and applications - aspirations and concerns about CCUS - how views towards CCUS differ in geographical areas where it may be developed in comparison to geographical areas where development is less likely - citizens' expectations in relation to the benefits and impacts of CCUS deployment in local areas This dialogue was commissioned by BEIS with support from UKRI's Science wise programme. It was designed and delivered by Traverse and evaluated by Ursus consulting	https://www.gov.uk/government/publications/carbon-capture-usage-and-storage-ccus-public-dialogue	UK CCUS Research
2	Framing effects on public support for carbon capture and storage	Lorraine Whitmarsh, School of Psychology, Cardiff University	Studying people's perceptions of CCUS depending on how the subject was framed	https://www.nature.com/articles/s41599-019-0217-x	UK CCUS Social
3	Developing a triple helix approach for CO2 utilisation assessment	Stephen McCord, Katy Armstrong , Peter Styring , Sheffield	This framework contributes a new aspect to the development of holistic sustainability assessment methodologies for CDU by enabling a triple helix to be created between LCA, TEA and social impact assessment (SIA). Therefore, the triple helix approach will enable trade-offs between environmental, economic and social impacts to be explored, ultimately enhancing effective decision making for CDU development and deployment	https://pubs.rsc.org/en/content/articlelanding/2021/FD/D1FD00002K	Found via Tyndal centre
4	Beyond Social Acceptability: Applying Lessons from CCS Social Science to Support Deployment of BECCS	Clair Gough	Paper highlighting framing as a critical factor in how society responds to BECCS technologies and argue that making the case for BECCS as a means of extending mitigation to make a 'net zero' goal achievable could be the key to its acceptable and sustainable deployment	Beyond Social Acceptability: Applying Lessons from CCS Social Science to Support Deployment of BECCS | SpringerLink	UKCCRC
5	Identifying Social Indicators for Sustainability Assessment of CCU Technologies: A Modified Multi-criteria Decision Making	Parisa Rafiaani	There is a lack of systematic social impact research in the CCU field due to the difficulty of identifying and quantifying social aspects through the entire life cycle of products. Using a multi-criteria decision-making tool, the article concludes that the indicators related to "end of life responsibility" and "transparency" within a CCU company achieved the highest rank affecting the consumers group, whereas "fair salary" and "equal opportunities/discriminations" were determined as the most relevant impact categories for the workers. For the local community group, "secure living conditions" and "local employment" received the highest priority from the experts' point of view. Furthermore, "health and safety" considerations were identified as one of the most important criteria affecting all three groups of stakeholders. The ranking list of the main social indicators identified in our study provides the basis for the next steps in the social sustainability assessment of CCU technologies; that is, data collection and impact assessment	https://link.springer.com/article/10.1007/s11205-019-02154-4	Social Impact CCUS
6	Evaluation of a public dialogue on Carbon Capture Utilisation and Storage (CCUS)	Anna MacGillivray (Ursus consulting for BEIS and Science Wise)	Independent evaluation of a public dialogue to explore attitudes towards CCUS	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1040626/evaluation-of-a-public-dialogue_on-ccus.pdf	
7	Contested framings of greenhouse gas removal and its feasibility: Social and political dimensions	Laurie Waller, Tim Rayner, Jason Chilvers, Clair Amanda Gough, Irene Lorenzoni, Andrew Jordan, Naomi Vaughan	Comprehensive review of 78 studies on social impacts of Greenhouse gas removal, especially focus on BECCS and afforestation. Highlights Social and political acceptability and responsible development framings about the topic	https://wires.onlinelibrary.wiley.com/doi/epdf/10.1002/wcc.649	Found via Tyndall centre

2.1 Research Projects

#	Project name	Technology name	Leading participants	Description of project	Capture	Utilisation	Transport	Storage	TRL	Year	Website	Search terms and Source of data
1	Capture: A2b, Pilot esting #2	Capture	Cranfield University	Cranfield University will use its extensive pilot plant facilities to demonstrate the use of unconventional sorbents and oxygen carriers, including chemical looping materials developed in the research project A1b (though not pressurised in this work). Systems to be tested will include pelletised sorbents and carriers using CaO and other binders	x				7	2019-22	https://ukccsrc.ac.uk/research/core-research-projects/capture-a2b-pilot-testing-2/	UKCCSRC Funded project
2	Combined systems and capture: AC3, Detailed models	Capture	University of Cambridge	Model/simulate the chemical plants that do the carbon capture. For new materials this are design models of plants that have yet to be built. The aim is to say whether proposed new processed and methods will compete against current processes	x				1-3	2019-22	https://ukccsrc.ac.uk/research/core-research-projects/ac3-detailed-models/	UKCCSRC Funded project
3	Capture: AC5, Reduced Order Models (ROMs)	Capture	University of Sheffield	Developing new and simpler models, which will be able to accurately predict the behaviour of post-combustion capture process	x				1-3	2019-22	https://ukccsrc.ac.uk/research/core-research-projects/ac5-roms/	UKCCSRC Funded project
4	Launch	Capture	EU+USA programme, Edinburgh, Sheffield	Looking at accelerating the implementation by approaching Amine solvent degradation. Using the PACT plant and the SCCS facilities to measure degradation	x				4-6	2019-22	https://launchccus.eu/	SCCS
5	Advancements in mixed amine atmospheric kinetic models	Capture	University of Sheffield	This research will hopefully gain a better idea of the behaviour of the emitted solvents, AMP and PZ, so that their safety profiles can be assessed. It should benefit government regulatory bodies, such as the Environment Agency, as well as power generators running natural gas combined cycle power plants with carbon capture and storage; industry which is large scale carbon dioxide emitters requiring in the future carbon capture and storage; and academics involved in atmospheric chemistry modelling	x				1-9	2021	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2021/dr-kevin-hughes-university-of-sheffield/	UKCCSRC Flexible Funding Projects 2021
6	Autarkic embedded Direct Air Capture for breakthrough cost reductions	Capture	University of Nottingham	In alignment with UKCCSRC's research needs identified recently (e.g. low concentration residual waste, containment challenges for smaller emitters, and cost reductions of CCS etc), this study aims to examine the feasibility of a new DAC technology that can potentially deliver major cost reductions by harvesting and using essentially any sources of waste heat at above ambient temperatures, filling a knowledge/technology gap that has never been investigated	x				1	2021	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2021/dr-chenggong-sun-university-of-nottingham/	UKCCSRC Flexible Funding Projects 2021
7	Development of an energy-efficient and cost-effective catalytic regeneration system in the post-combustion CO2 capture process	Capture	University of Hull	The proposed project is predicted to deliver a 30-40% cost reduction of the PCC process. Identified benefits to various groups will include: (a) The researchers will publish a dataset of the properties of 100 catalysts (derived from molecular simulation model) on open access, which may benefit other researchers worldwide. This will support ongoing research in this subject by other researchers. The process model will also provide useful insight for other researchers. (b) The techno-economic data including the cost of capture, energy penalty and so on, that will come from this research will support decision-making by policymakers. (c) This work will provide useful insight for technology developers on catalysed regeneration. (d) The cost impact of low carbon technology transition will be borne by the wider society. The proposed project offers a cheaper route for reaching low carbon transition goals and therefore lessen the cost burden for the wider society	x				1	2021	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2021/dr-eni-oko-university-of-hull/	UKCCSRC Flexible Funding Projects 2021

8	Fugitive amine emission scrubbing using electrostatic precipitation	Capture	Cranfield University	This study will utilise a conductor-like polarizable continuum model via DFT calculations to determine dipole moments, molecular geometry optimisation of different amines and then calculate molecular force interactions within different electric field strengths to determine potential design constraints for a fugitive amine electrostatic precipitator. These calculations will provide the starting point for the mechanical design of a prototype for the fugitive amine electrostatic precipitator	x				1	2021	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2021/flexible-funding-2021-dr-peter-clough-cranfield-university/	UKCCSRC Flexible Funding Projects 2021
9	PCC-CARER: Post-Combustion Capture – Cost And Residual Emission Reduction	Capture	University of Sheffield	This research is looking at a number of measurements to feed into enhanced performance for post-combustion capture. Its objectives are: To obtain novel pilot-scale measurements on the TERC Amine Capture Plant for post-combustion amine plant operation with low lean loadings and liquid flows, conditions that are now required to obtain cost-effective operation at 95%+ CO2 capture levels will be automatically published on EPSRC's website in the event that a grant is awarded	x				3-5	2021	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2021/prof-jon-gibbins-university-of-sheffield/	UKCCSRC Flexible Funding Projects 2021
10	Pilot Scale Carbon Capture using Solid Sorbents PICASSO	Capture	University of Nottingham	This project aims to demonstrate that robust metal organic framework sorbents (MOFs) can capture over 100kgs CO_2 /day from actual flue gas from the Drax Incubator site at Drax Power Station in Selby, North Yorkshire	x				6	2021	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2021/prof-ed-lester-picasso/	UKCCSRC Flexible Funding Projects 2021
11	Scale up of F4_MIL-140(Ce) for next generation carbon capture (F4-Next-CC)	Capture	Swansea University	The main aim of the project is to upscale the water-based synthesis of F4_MIL-140(Ce) 500-fold using commercial reagents and equipment, and investigate and evaluate the potential for the formation of monoliths of the material since shaping of powders is required in large-scale CCS units. The newly discovered Cerium-based MOF, F4_MIL-140(Ce), is ideally suited for industrial CCS since it displays an exceptional CO2/N2 selectivity, amongst the highest reported for solid sorbents	x				4	2021	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2021/dr-enrico-andreoli-swansea-university/	UKCCSRC Flexible Funding Projects 2021
12	Co-Cap: Collaboration on commercial capture	Capture	Prof Jon Gibbins, University of Sheffield	The team involved in this proposal are linked with both the BEIS and the US DOE FEED studies above and other UK PCC deployment activities and will use funding to build on these studies to cover additional topics of immediate policy and commercial interest, in particular enhanced capture levels (95% and above) for net-zero. Broad dissemination of OA PCC information and discussions between industry and academic experts will also be supported by open workshops and detailed information on the UKCCSRC website. As well as contacts with UK industry the applicants are also able to input to ACT projects on PCC (ALIGN and LAUNCH), to the CCUS Mission Innovation initiative and programmes in China, Mexico and other key UK CCUS partners overseas	x				5	2020	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2020/prof-jon-gibbins-university-of-sheffield/	UKCCSRC Flexible Funding Projects 2020
13	CO2-FROST: CO2 frost formation during cryogenic carbon capture with tomography analysis	Capture	Dr Carolina Font-Palma, University of Chester	This project investigates a cryogenic carbon capture method that does not require chemicals, is capable of high CO2 removal levels and delivers a high purity CO2, which could be further used in the food industry or to produce chemicals. The cryogenic process involves very low temperatures (around -100C or below) that cause CO2 to freeze on the surface of beads previously chilled	x				1	2020	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2020/carolina-font-palma-university-of-chester/	UKCCSRC Flexible Funding Projects 2020

14	Evaluation of different CCUS systems based on the MCFC technology for decarbonising the power generation sector	Capture	Prof Lin Ma, University of Sheffield	This proposal is focused on a disruptive carbon capture process, namely the Molten Carbonate Fuel Cell (MCFC) technology. Unlike other capture technologies that absorb energy, MCFC is an active unit that generates energy, resulting in reduced capture energy penalties. The study focuses on the decarbonisation of the power sector, particularly the natural gas combined cycle plants	x				1	2020	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2020/prof-lin-ma-university-of-sheffield/	UKCCSRC Flexible Funding Projects 2020
15	Biomass combustion ash in carbon capture	Capture	Dr Salman Masoudi Soltani, Brunel University London	This research aims to investigate the potential of raw and surface-modified UK-based biomass ash (BCA) as adsorbent in post-combustion CO2 capture. In the first phase of the project, industrial BCA generated in the UK will be fully characterised and then modified to increase its adsorption capacity and kinetics for CO2 capture. In phase 2 of the project, the actual adsorption/desorption process will be studied via thermogravimetric analysis and a fixed-bed column, designed and built at Brunel University London	x	x			1	2020	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2020/flexible-funding-2020-salman-soltani/	UKCCSRC Flexible Funding Projects 2020
16	Accelerating basic Solid Adsorbent Looping Technology	Capture	Professor Snape, University of Nottingham	Not yet published	x				1	2021	http://www.act-ccs.eu/act3	ACT3
17	Align CCUS	Capture, Storage, Transport, Utilisation	EU wide programme, including Heriot Watt, BGS, ICL, PACT, University of Edinburgh	The multi-partner ALIGN-CCUS project unites science and industry in a shared goal of transforming six European industrial regions into economically robust, low-carbon centres by 2025. Our international partnership of 34 research institutes and industrial companies has secured European and national funding for six specific but interlinking areas of research into CCUS	x	x	x	x	1-7	2017-2021	https://www.alignccus.eu/	Found Through university websites
18	Combined systems & capture: AC1, BECCS	Capture	University of Sheffield	Pilot testing will performed using the TERC facilities to demonstrate, for greenfield applications, the potential of oxy-fuel capture technology	x				5-6	2019-22	https://ukccsrc.ac.uk/research/core-research-projects/core-research-projects-ac1-beccs/	UKCCSRC Funded project
19	Combined systems & capture: AC2, Advanced high-efficient cycles using gas turbines with S-CO2 or direct oxy-fired CCGT-CCS	Capture	University of Sheffield Cardiff	Investigating a novel system for CO2 capture from a gas turbine. The use of supercritical CO2 as a combustion moderator is a challenging area of scientific research, since the operating conditions require pressures far beyond existing engine technologies. The understanding of properties such as heat transfer and molecular diffusion are importing in designing S-CO2 cycles and there is much scope for fundamental research to build the technical knowledge base	x				5-6	2019-22	https://ukccsrc.ac.uk/research/core-research-projects/core-research-projects-combined-systems-capture-ac2-advanced-high-efficient-cycles-using-gas-turbines-with-s-co2-or-direct-oxy-fired-ccgt-ccs/	UKCCSRC Funded project
20	Capture: AC4, Integration options for hydrogen and clean power synergies null	Capture	University of Edinburgh	This work investigates the scope for cost reduction by integration to use a single post-combustion carbon capture (PCC) system for both the SMR and the CCGT power plant	x				1-3	2019-22	https://ukccsrc.ac.uk/research/core-research-projects/ac4-integration-options-hydrogen-clean-energy-synergies/	UKCCSRC Funded project
21	Techno-economics of biomass combustion products in the synthesis of effective low-cost adsorbents for carbon capture	Capture	Brunel University London	This research will be investigating the viability of BCP valorisation in in-situ decarbonisation of biomass combustion facilities such as those at Drax Power Plant where the BCP has been sourced	x				1	2021	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2021/dr-salman-masoudi-soltani-brunel-university-london/	UKCCSRC Flexible Funding Projects 2021

22	Cucurbit[5]uril-incorporated photocatalytic membrane for carbon capture and utilisation	Capture, Utilisation	Prof Junwang Tang, University College London	CB[5], a new type of polymer, has an uptake capacity of 26 mL g-1 for CO2, comparable to MOFs, while much higher than that of the uptake capacity for N2, O2 and CO, thus highly selective for CO2 adsorption. Moreover, the carbonyl groups at the portal of CB[5] allow the formation of complexes with cations such as Co2+, Ni2+, Cu2+, Pb2+, Zn2+,Cd2+, Cr2+ and Fe2+, leading to potential catalytic sites for captured CO2 to be in-situ converted to valuable chemicals. In addition, CB[5] are stable in the presence of water. The project aims not only to synthesise a CB[5]-incorporated membrane for CCS but also to embed photocatalysts (e.g. Cu2O, C3N4) into the CB[5]-incorporated membranes for carbon capture and utilisation (CCU). Thus a photocatalytic membrane reactor will be generated and investigated in the project for CO2 conversion to high value chemicals	x	x			1	2020	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2020/flexible-funding-2020-prof-junwang-tang-ucl/	UKCCSRC Flexible Funding Projects 2020
23	Capture: A1, Materials development	Capture	Imperial College London	This research focuses on two types of CO2 sorbents with high degree of tunability that are at different levels of maturity in terms of testing and manufacturing. These materials include: metal-organic frameworks (MOFs) materials for post-combustion and industrial capture, and also inorganic porous materials for chemical looping combustion (CLC)	x				4	2019-22	https://ukccsrc.ac.uk/research/core-research-projects/a1-materials-development/	UKCCSRC Funded project
24	Capture: A2a, Pilot testing #1	Capture	University of Nottingham	A pilot-scale facility for low temperature solids adsorbent looping technology (SALT)	x				7	2019-22	https://ukccsrc.ac.uk/research/core-research-projects/core-research-projects-capture-a2a-pilot-testing-1/	UKCCSRC Funded project
25	Systems & Policy: CAB1 - Cross-cutting value of CCS	Policy	Imperial College London, UCL	We will quantify System Integration Costs (SIC) of CCS and other low carbon technologies under different future development scenarios, assess the competitiveness of CCS against other low carbon generation technologies and determine key factors/parameters that will drive SIC and enhance or limit the competitiveness of CCS					N/A	2019-22	https://ukccsrc.ac.uk/research/core-research-projects/cab1-cross-cutting-value-ccs/	UKCCSRC Funded project
26	Systems & Policy: CA1 - BECCS within the energy system	Policy	Imperial College London	Building on detailed (first principles) technical modelling of oxy- and amine-BECCS[1] and drawing on the work in AC1 BECCS, we conduct a socio-techno-economic analysis of the potential role for BECCS in the larger energy system	x			x	N/A	2019-22	https://ukccsrc.ac.uk/research/core-research-projects/ca1-beccs-within-energy-system/	UKCCSRC Funded project
27	Systems & Policy: CB1 - Social license to operate	Social Impact	Tyndall Centre at University of Manchester	Firstly, we apply the concept of 'protective spaces' from sustainability transition management to the five industrial clusters to explore the extent to which this approach will effectively enable the wide-scale deployment of CCUS. Secondly, we explore the conditions necessary for establishing a social license to operate (SLO) for CCUS and the implications for the future within industry and for BECCS					N/A	2019-22	https://ukccsrc.ac.uk/research/core-research-projects/cb1-social-license-to-operate/	UKCCSRC Funded project
28	**SECURe**	Storage	BGS, Heriot Watt, Edinburgh, Nottingham	The SECURe project will gather scientific evidence relating to monitoring the environment and mitigating risk in order to guide subsurface geoenergy development. The three-year project will produce a set of best practice recommendations for establishing environmental baseline conditions for the geological storage of anthropogenic CO2, including outputs addressing how to develop effective communications strategies with different stakeholder groups				x	1-3	2019-2021	https://www.securegeoenergy.eu/	SCCS

29	Feasibility study into quantum technology based gravity sensing for CCS	Storage	University of Birmingham	This project will baseline the requirements for quantum technology-based gravity monitoring of CCS and could lead to the first demonstration of a quantum technology-based gravity sensor being used for this purpose. This would open up new applications for the quantum sensor community, with new pathways for commercialisation of ultra-precise quantum sensors. In the medium to long term, the research will benefit the CCS and geophysics communities, as a quantum enhanced sensor would provide an unprecedented amount of high-quality data, which when used in conjunction with existing monitoring technology will enable a significant leap in our ability to understand and manage CCS storage sites, enhancing understanding and making a contribution to preventing the many negative impacts expected from climate change				x	1	2021	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2021/flexible-funding-2021-dr-michael-holynski-university-of-birmingham/	UKCCSRC Flexible Funding Projects 2021
30	Sensor ernabled seabed landing AUV nodes for improved offshore CCS monitoring	Storage	National Oceanography Centre Southampton	Experimental studies have shown that detection of a carbon dioxide leakage from the seafloor can be done with sensors mounted on either autonomous underwater vehicles (which can be expensive) or on fixed installations (which requires many installations to achieve broad spatial coverage). Recent technological developments have led to a low-cost hybrid system which combines autonomous underwater vehicles and fixed installations technology, so called 'flying nodes'. These flying nodes can remain on the seafloor for up to a year and, even more important, they are designed to work in a swarm of up to 3000 vehicles, hence can survey a large area in significantly less time than the traditional underwater vehicles. This project aims to show that the integration of chemical sensors and flying nodes is feasible and beneficial				x	2	2021	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2021/dr-anna-lichtschlag-national-oceanography-centre/	UKCCSRC Flexible Funding Projects 2021
31	SCARP North Sea: Storage Challenge and Reserve Provision, a fundamental gigatonne CO2 challenge for European net zero	Storage	Prof Stuart Haszeldine, University of Edinburgh	A narrative compilation will be produced, estimating the bottom-up effort required to make ready storage gigatonnes for the UK, and North Sea as predicted by bottom-up modellers, and compared to the top-down policy-pull requirements				x	N/A	2020	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2020/flex-2020-stuart-haszeldine-edinburgh/	UKCCSRC Flexible Funding Projects 2020
32	Storage & Transport: B1, Pressure propagation & control	Storage	University of Edinburgh, Imperial college London, University of Cambridge, BGS	To improve our ability to predict the volume of CO2 which can be stored, we are modelling the propagation of pressure throughout the reservoir				x	1-3	2019-22	https://ukccsrc.ac.uk/research/core-research-projects/storage-b1-pressure-propagation-control/	UKCCSRC Funded project
33	Storage & Transport: B2, CO2 migration & storage	Storage	University of Edinburgh, Imperial college London, University of Cambridge, BGS	This research project has been carefully designed to answer some fundamental questions about the behaviour of a CO2 plume				x	1-3	2019-22	https://ukccsrc.ac.uk/research/core-research-projects/storage-transport-b2-co2-migration-storage/	UKCCSRC Funded project
34	Storage & Transport: B3, CO2 modelling assessment	Storage and Transport	University of Edinburgh, Imperial college London, University of Cambridge, BGS	This project plans to simulate 1 Gt CO2 storage from inception through optimised injection and pressure management, to policing and managing of CO2 dispersion, dissolution, and eventual handover and abandonment			x	x	1-3	2019-22	https://ukccsrc.ac.uk/research/core-research-projects/core-research-projects-storage-transport-b3-co2-modelling-software-assessment/	UKCCSRC Funded project

35	Storage & Transport: B4, Scoping/Development of a proposed CO2 geolab	Storage	University of Edinburgh, Imperial college London, University of Cambridge, BGS	Onshore CO2 injection labs act as locations to calibrate injection mode, or test new equipment. The UK has no CO2 facility. A UKCCSRC scoping study has provisionally identified the Ellesmere Port area as having viable subsurface geology for an onshore deep injection pilot project				x	1	2019-22	https://ukccsrc.ac.uk/research/core-research-projects/b4-scoping-development-proposed-co2-geolab/	UKCCSRC Funded project
36	Forge	Transport	TWI	Part of a Large EU Horizon 2020 project, looking at compositionally complex materials for CO2 transport			x		1-3	2020	https://www.twi-global.com/media-and-events/press-releases/2021/carbon-capture-utilisation-and-storage-why-does-it-matter	Horizon 2020, UK CCUS Transport Research
37	PilotSTRATEGY	Storage	EU programme across 5 countries	University of Edinburgh doing Geocharacterisation PilotSTRATEGY aims to advance understanding of deep saline aquifers (DSA) for geological CO2 storage in five European industrial regions. DSAs have much promise and potential for CO2 storage, yet are not well studied. There is a need to increase knowledge of these sites to enable faster deployment of CCS				x	1-5	2020	https://pilotstrategy.eu/	SCCS
38	Advanced multitemporal modelling and optimisation of CO2 transport and storage networks	Storage and Transport	Professor Korre, Imperial College London	Not yet published			x	x	1	2021	http://www.act-ccs.eu/act3	ACT3
39	Recovering liquefaction cost of captured carbon dioxide by cold energy utilisation and electric power generation	Transport	Dr Kumar Patchigolla, Cranfield University	This research aims to perform technical feasibility and economic viability of a novel cold storage concept to recover some of the energy cost on liquefying CO2 for shipping transportation. Although cold storage concept introduced a benefit for energy management in the chain, it was limited to specific scenarios involving the presence of a gas production site and an oxy-fuel capture process. Developing solutions of implementation for cold energy utilisation and electric power generation prior to the injection point could enhance economic feasibility of the chain by recovering liquefaction cost of captured carbon dioxide			x		1	2020	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2020/flexible-funding-2020-dr-kumar-patchigolla-cranfield-university/	UKCCSRC Flexible Funding Projects 2020
40	Monitoring of CO2 flow under CCS conditions through multi-modal sensing and machine learning	Transport	Prof Yong Yan, University of Kent	This project aims to evaluate a cutting-edge technology for the monitoring of CO2 flow under CCS conditions. The project will start with the establishment of a novel multi-modal sensing system incorporating Coriolis, ultrasonic, differential-pressure and acoustic emission sensors as well as temperature and pressure transducers. Data-driven models based on convolutional neural network and Bayesian statistical learning algorithms will be developed to fuse the outputs from the sensors in order to provide the measurements of flow characteristics in CO2 pipelines or detect the leakage plums from confined CO2 units. An extensive experimental programme will be undertaken to acquire practical datasets under a wide range of CCS conditions to train and validate the machine learning models			x		2	2020	https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2020/flexible-funding-2020-yong-yan-kent/	UKCCSRC Flexible Funding Projects 2020
41	CoCaCO2La	Utilisation	Damien Kirkpatrick, TWI	Not yet published		x			1	2021	http://www.act-ccs.eu/act3	ACT3

2.2 Research Networks

#	Research network name	Main participants	Description of research activity	Website	Search terms and Source of data
1	UK CCS RC	University of Sheffield University of Cambridge Imperial College Nottingham BGS University of Edinburgh Manchester Cranfield Cardiff Manchester Strathclyde UCL	UK CCS research body, bringing together a wide range of academic institutions to coordinate research. Coordinate and run funding from EPRSC for all aspects of CCUS. Promotes UK CCUS research, including holding MoU's with CCUS organisations in 6 other countries (Australia, Canada, China, Netherlands, South Korea, USA)	https://ukccsrc.ac.uk/what-we-do/international/	UKCCSRC
2	Scottish CCS Centre	British Geological Survey, Heriot-Watt University, the University of Aberdeen, the University of Edinburgh, the University of Glasgow and the University of Strathclyde	SCCS is the largest CCS research group in the UK, providing a single point of coordination for CCS research, from capture engineering and geoscience to social perceptions and environmental impact through to law and petroleum economics	https://www.sccs.org.uk/about-us	SCCS
3	Accelerating CCS Technologies (ACT)	The ACT members are funding agencies from: The Alberta province in Canada, Denmark, France, Germany, Greece, India, Italy, the Netherlands, Norway, the Nordic Region, Romania, Spain, Switzerland, Turkey, UK, and the USA. The Research Council of Norway (RCN) is coordinating ACT.	ACT is a global CCS research funding group, originally designed to run from 2016-21, but has since been extended under ACT3 - Funding from both UK and India, among others. They have funded a wide range of projects	http://www.act-ccs.eu/act3	ACT CCS
5	UKERC Energy Data Centre: Data Catalogue	UKERC	Database containing existing data stores	https://ukerc.rl.ac.uk/DC/cgi-bin/edc_search.pl?GoButton=Related&WantComp=73	UKERC
6	CCSA	UK and international technology and professional service firms, including Consultancy, Law, National Grid, Oil and Gas, Investors	UK Trade Association for the CCUS industry, covering more than 80 companies. This includes Law Firms, SMEs, O&G majors, from all parts of the value chain	https://www.ccsassociation.org/membership/our-members/	UK CCS Trade association
7	CO2Chem	Lead by University of Sheffield	A previous EPSRC Grand Challenge Network that was focused on delivering research into the utilisation of CO2 as a chemical feedstock	http://co2chem.co.uk/	CO2Chem

2.3 Stakeholders

#	Stakeholder name	Description of stakeholder involvement in CCUS	Examples of companies	Website
1	UK Government	Responsible for regulation, and policy in the sector, including deploying fund		https://www.gov.uk/environment/oil-and-gas-carbon-capture-and-storage
2	Department for Business, Energy & Industrial Strategy (BEIS)	Responsible for Industrial Strategy related to CCUS, clusters mapping, deployment plans, business models development etc	BEIS	https://www.gov.uk/government/publications/carbon-capture-usage-and-storage-ccus-business-models
3	North Sea Transition Authority (NSTA)	Responsible for oil and gas regulation as well as carbon storage in the North Sea	North Sea Transition Authority	https://www.nstauthority.co.uk/the-move-to-net-zero/carbon-capture-and-storage/
4	Enviromental Agency	Responsible for enviromental aspects related to CCUS. Published a guidance document outlining recommended techniques for CCUS	Enviromental Agency	https://www.gov.uk/government/news/guidance-published-on-new-carbon-capture-technologies
5	British Geological Survey (BGS)	Responsible for surveying of potential geological structures for carbon storage. Have published online a storage database identying storage potential deep under UK seabed	BGS	https://www.bgs.ac.uk/geology-projects/carbon-capture-and-storage/
6	Crown Estate			
7	Carbon Capture and Storage Association (CCSA)	Trade association promoting commercial deployment of CCS	CCSA	https://www.ccsassociation.org/about-us/who-we-are/
8	Climate Change Committee (CCC)	Independent, statutory body whose purpose is to advise the government and report to the Parliament on progress made	CCC	https://www.theccc.org.uk/2018/11/28/ccc-welcomes-governments-recommitment-to-carbon-capture-and-storage-technology/
9	Universities	Universities leading CCUS research	University of Sheffield, University of Cranfield and Imperial College London are examples. Refer to refer to tab "1.1 Universities" for a more detailed list	Please refer to tab "1.1 Universities" to access the websites of each university
10	Research Institutes	Institutes leading CCUS research	UK CCS RC, BGS, TWI are examples. Refer to "1.2 R&D Institutes " for a more detailed list	Please refer to tab "1.2 R&D Institutes " to access the websites of each institute

11	Research Networks	Research Networks focused on CCUS	UK CCS RC and Scottish CCS Centre are examples. Refer to the tab "2.3 Research Networks" for a more detailed list	Please refer to tab "2.3 Research Networks" to access the websites of each network
12	UK Reasearch and Innovation (UKRI)	Funding for CCUS research in several development stages thorugh challenages and breader programs	UKRI	https://www.ukri.org/what-we-offer/browse-our-areas-of-investment-and-support/carbon-capture-and-storage/
13	HM Treasury	Government's economic and finance ministry. Published National Infrastructure Strategy, including net-zero strategy (including CCUS) as part of the levelling-up agenda and recovery from COVID		https://www.gov.uk/government/publications/national-infrastructure-strategy
14	Small and Medium Enterprises (SMEs)	Invovelved in CCUS deployment	Carbon Clean, OCO Technologies, Carbon8, etc. A detailed list of the UK SMEs is provide on tab "1.3 SMEs"	Please refer to tab "1.3 SMEs" to access the website of each SME
15	Large companies	Companies involved on CCUS commercial deployment	Johson Matthey, BP, Aker are examples. Refer to the tab "1.4 Large Enterprises" for a detailed list of the companies	Please refer to tab "1.4 Large Enterprises" to access the websites of each company
16	Oil and Gas Climate Initiative (OGCI)	Oil and Gas industry initiative commited to climate change. Launched a kickstarter initiative in 2019 to help stablish multiple low-carbon hubs worldwide	BP, Chevron, CNPC, Eni, Equinor, Aramco, ExxonMobil, Oxy, Petrobras, Repsol, Shell, Total Energies	https://www.ogci.com/about-us/who-we-are/
17	Capture companies	Companies developing initiatives focused on capture	Johnson Matthey,Drax,Mitsubishi,Shell	Please refer to tab "1.4 Large Enterprises" for more details
18	Companies in utilisation	Companies developing initiatives on utilisation	Tata Chemicals	Please refer to tab "1.4 Large Enterprises" for more details

19	Storage & Transport Companies	Companies developing initiatives on storage and transport	Shell,ENI, Equinor, BP, Total Energies, National Grid (Transport), Kellas (Transport)	Please refer to tab "1.4 Large Enterprises" for more details
20	Companies who will produce CO2	Companies developing initiatives on CCUS	Industrial players such as hydrogen producers, oil refineries, power generation plants etc	
21	Project Management and Development Companies	Companies focused on CCUS project managements and development	Storegga, Progressive energy	https://www.progressive-energy.com/what-we-do
22	Investors in CCUS Tech	Several Oil and Gas companies have been investing in CCUS technology development. There are also some venture capital investors. UK government has funded several projects as well	BP, Chevron, Centrica, OGCI Climate Investments, Imperial Innovations, Barclays Sustainable and Impact Banking	https://imperial.tech/
23	Finance of projects		UK Infrastructure Bank	https://www.ukib.org.uk/where-we-invest
24	Insurance	This is still a developing area. As projects start being deployed there will be more activity in the field	UK Government, MarshMacLennan	https://www.marsh.com/uk/industries/energy-and-power/insights/carbon-capture-in-uk-risk-considerations.html
25	CCUS Clusters	Cross-sectorial organisationsaiming at CCUS deployment in industrial Hubs. Each cluster has a different consortium	HyNet, East Coast, Accorn, South Wales Industrial Cluster (SWIC)	Please refer to "1.5 Projects" to access the webistes of each cluster
26	Community (local to CCUS site/ nation wide)	Local goverments where the CCUS are likely to implmented, general public		
27	Enviromental NGOs	Climate NGOs influencing public opinion		
28	Department for Education (DfE)	Skilling programs to support energy transition. Carried out the "Green Jobs" Taskforce in conjuction with BEIS	DfE	https://www.gov.uk/government/organisations/department-for-education
29	OPITO	Global skills body for the energy industry. Leading the development of an integrated people and skills plan to support the UK Government's North Sea Transition Deal's rollout	OPITO	https://opito.com/
30	Energy Skills Alliance	Cross-industry group led by OPITO, bringing together leaders from across the oil and gas, renewables, nuclear and refining industries, as well as representation from within regulators, governments and trade unions		https://opito.com/energy-transition/energy-skills-alliance

1.1 Universities

#	University Name	Campus location(s)	Description of CCUS capability	Key CCUS research areas				TRL	Website	Search terms and Source of data
				Capture	Utilisation	Transport	Storage			
1	IIT Bombay	Mumbai	The research areas are strongly focussed in pre-combustion and post-combustion capture, storage and utilization technology	x	x		x	1	www.iitb.ac.in	
2	IIT Roorkie	Roorkie	Reservoir engineering and geomechanics in CCS				x		https://www.sciencedirect.com/science/article/abs/pii/S092134492100433X#!	Carbon capture, Electricity, Source-sink matching Enhanced oil recovery (EOR)
3	NEERI - Nagpur	Nagpur	The institution has been researching Biological and chemical sequestration technology	x					https://www.neeri.res.in/#googtrans(en|en)	CO2 sequestration in India, CCUS, carbon capture
4	National Geophysical Research Institute (NGRI	Hyderabad	Their research involves sequestration methods in geological environment	x					https://www.ngri.res.in/	Carbon capture, sequestration , source
5	cal Research Institute	New Delhi	Policy briefs for CCUS in India	x				2	http://icrier.org/pdf/Policy_Brief_11.pdf	Carbon capture, Policy
6	RKDF University	Bhopal	Feasibility study of CCUS in Thermal Power Plant	x				2	https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3366144	Carbon capture, Sequestration, Post Combustion Carbon Capture, Concentrated solar plant, MEA solvent, Energy penalty
7	Jawaharlal Nehru Centre for Advanced Scientific Research	Bengaluru	Research and development of Carbon capture and utilisation	x	x				https://www.jncasr.ac.in/home	Carbon capture process, source is DST,India documents
8	https://www.iiserkol.ac.in/web/en/#gsc.tab=0	Kolkata	Research on carbon capture and C02 separation technology	x					https://www.iiserkol.ac.in/web/en/#gsc.tab=0	CCUS research in India
9	CSIR-National Chemical Laboratory	Pune	They research around pre-combustion carbon removal technologies	x					https://www.ncl-india.org/	

10	CSIR-Indian Institute of Petroleum	Dehradun	Their research involves methods of pre combustion carbon capture and removal technology	x				2	https://www.iip.res.in/	Carbon removal technologies, CCUS , science direct
11	Indian Institute of Science	Delhi	Carbon capture and removal from synthesis gas	x	x				https://iisc.ac.in/	Carbon Capture in India
12	CSIR –Central salt & Marine Chemicals Research Institute	Bhavnagar	Their research are involves carbon removal and utilisation methodologies from agro-residues and microporous materials	x	x				https://www.csmcri.res.in/	Sequestration in India , Carbon removal
13	Department of Chemical Engineering, Indian Institute of technology	Delhi	Integrated CO2 absorption and conversion to methanol in slurry phase reactors using metal complexes as catalyst	x	x				https://home.iitd.ac.in/	Carbon capture research in India
14	Pondicherry University (Central University)	Pondicherry	Utilisations technology using hybrid multi electrode plasma reactors		x				https://www.pondiuni.edu.in/	CCUS research in India , carbon capture
15	Pandit Deendayal petroleum University	Gujarat	Their research involves carbon utilisation	x	x				https://pdpu.ac.in/	Carbon utilization technology
16	Vaidya Institute of Chemical Technology	Mumbai	Area of research involves carbon capture technology from solvents	x					https://www.ictmumbai.edu.in/emp_profiledetail.aspx?nDeptID=eg	Carbon capture
17	CSIR-Indian Institute of Chemical Technology	Hyderabad	Carbon capture methods from Combined sorbent catalyst Material (CSCM)	x					https://www.csir.res.in/indian-institute-chemical-technology-hyderabad	
18	Marathwada Institute of Technology (MIT-E)	Aurangabad	Their research capabilities includes carbon capture and utilisation into gas sensors, hierarchical heterostructures, photocatalysis	x	x				https://engg.mit.asia/	
19	Indian Institute of Technology	Gandhinagar	Carbon capture technology from nontoxic materials and solid wastes	x					https://iitgn.ac.in/	
20	National Institute of Technology	Tiruchirappalli	Carbon capture and utilisation technology using RuBisCohypermorphs and utilization in polymers	x	x				https://www.nitt.edu/	

21	BITS Pilani K K Birla	Goa	Carbon capture and utilisation technology for power generation	x	x				https://www.bits-pilani.ac.in/Goa/	
22	Indian Institute of Engineering Science and Technology	Shibpur	Carbon capture and storage in coal fields	x			x		https://www.iiests.ac.in/	
23	SSN College Of Engineering	Chennai	Post-combustion CO2 capture process	x					https://www.ssn.edu.in/	
25	Indian Institute of Technology ISM	Dhanbad	Research around carbon storage technology using composite materials				x		https://www.iitism.ac.in/	
26	Department of Ocean Engineering, IIT Madras	Chennai	Numerical modelling in CO2-ECBMR (Fundamental)				x	0	https://www.iitm.ac.in/	
27	Department of Civil Engineering, IIT Madras	Chennai	Offshore CO2 storage with ecological significance, UFCC				x		https://civil.iitm.ac.in/	
28	Department of Chemical Engineering, IIT Madras	Chennai	Chemical approach to CO2-EOR				x		https://che.iitm.ac.in/	
29	Department of Environmental Science and Engineering, IIT Bombay	Mumbai	They have been working the research areas of transport, TEA, LCA for CCS			x	x		https://www.esed.iitb.ac.in/	

1.2 R&D Institutes

#	Institute Name	Campus location(s)	Description of CCUS capability	Key CCUS research areas: Capture	Utilisation	Transport	Storage	TRL	Website	Search terms and Source of data
1	National Centre of Excellence - Carbon Capture, Utilization	Mumbai	The centre will work on the conversion of captured carbon dioxide to chemicals, CO2 transport, compression and utilization, as well as on enhanced hydrocarbon recovery as co-benefit pathways. The NCoE-CCU will also develop and demonstrate efficient CO2 capture from representative flue gas from the effluents of the power plant and biogas plant	x	x			0	https://www.iitb.ac.in/	Carbon capture in India, Source - newsonair.com
2	National Centre in Carbon Capture and Utilization	Bangalore	It is aimed to develop and demonstrate carbon capture and conversion by developing relevant materials and methodologies. These processes will be scaled up to pilot scale mode to produce hydrocarbons, olefins and other value-added chemicals and fuels. It will also work on reaching the technology readiness level on par with the commercial requirement at the industry level. The centre will promote the CCU research, provide training and consultancy and translate its research excellence into solutions with global economic and social impact	x	x			0	https://www.jncasr.ac.in/home	Carbon sequestration in India, source newsonair.com
3	Council of Scientific and Industrial Research, National Chemical Laboratory (CSIR-NCL)	Pune	Catalysis, Zeolites, Solid State Chemistry, Heterogeneous Catalysis	x	x				https://www.ncl-india.org/	CSIR CCUS, Carbon capture, carbon sequestration
4	Indian Association for the Cultivation Of Science	Kolkata	Homogeneous catalysis, CO2 activation	x	x				http://www.iacs.res.in/	CCUS in India, Carbon capture technology, carbon sequestration , novel catalysts
5	CSIR-Central Institute of Mining and Fuel Research	Dhanbad	Methane Emission and Degasification, Large scale storage, coal seam storage	x	x		x		https://cimfr.nic.in/	Carbon storage in coal mines, coal and CCUS
6	Indian Institute if Technology	Delhi	Research on capture technologies, utilization into valuable products and Storage monitoring technologies	x					https://home.iitd.ac.in/	Carbon capture, carbon storage, sequestration
7	National Geophysical Research Institute, NGRI	Hyderabad	Research on storage capacity and feasibility in Indian Geological formations . Also involved in carbon capture technology and novel methods	x			x		https://www.ngri.res.in/	Carbon storage in India, geologiocal formations and carbon
8	Centre of Excellence of Coal Research, BHEL	Tiruchirappalli	Research on storage capacity and feasibility in Indian Geological formations . Also involved in carbon capture technology and novel methods				x		https://www.bhel.com/bhels-centres-excellence	Carbon sequestration, Bhel , post capture combustion , oxyfuel combustion
9	National Environmental Engineering Research Institute, NEERI	Mumbai	Carbon capture and utilization technology	x	x				https://www.neeri.res.in/	carbon seqauestration , carbon capture, CCUS utilization, CO2 conversion

1.3 SMEs

#	Company name	Main location(s)	Description of CCUS capability	Key CCUS activity areas: Capture	Utilisation	Transport	Storage	TRL	Website	Search terms and Source of data
1	Indian Farmers Fertiliser Co-Operative	Aonla, UP	Indian Farmers Fertiliser Co-Operative is using MHI's CO_2 recovery process, with its KS-1™ amine solvent, to capture CO_2 at its urea manufacturing plant in Aonla, Uttar Pradesh. The system recovers CO_2 from the plant's natural gas-fired steam reformer flue gases, after which the gas is compressed and used for urea synthesis. The CO_2 absorber captures around 450 tonnes of CO_2 a day, and the facility has been in operation since 2006	x				9	https://www.iffco.in/en/production-unit-aonla	carbon capture technology, research, Co2 recovery , Source - web search
2	Indo Gulf Corporation Ltd	Jagdishpur	CO_2 is recovered from the flue gas of the ammonia reformer unit using a Fluor Econamine FGSM (Fluor) unit which helps to balance the NH_3/CO_2 requirements. This facility started operations around 1988 and produces 150 t/day CO_2 that is utilised in the manufacture of urea. This is a total reduction (in these particular months) of 9131 tonnes of CO_2 which would otherwise have been released into the atmosphere	x				9		carbon capture technology, research, Co2 recovery , Source - web search
3	Indian Farmers Fertiliser Co-Operative		The Indian Farmers Fertiliser Co-Operative has been recovering since 2006 CO_2 from natural gas-fired steam reformer flue gases at the Phulpur urea plant in Uttar Pradesh, India. The CO_2 is captured at a rate of 450 t/day before being compressed and re-used in urea synthesis. The plant uses Mitsubishi Heavy Industries proprietary KM CDR Process®	x				9		carbon capture technology, research, Co2 recovery , Source - web search
4	Carbon Clean Solutions	Mumbai, UK, US	Provides carbon dioxide (CO_2) separation technology for industrial and gas treating applications. The company's technology is used in power-plants, and steel, cement, fertilizer, chemical, and petrochemical industries for reducing CO_2 emissions	x				9		amine carbon capture india startup
5	Breathe Applied Sciences	Bangalore	Conversion of CO_2 to methanol and other chemicals	x	x			7	http://breathesciences.com/	https://www.jncasr.ac.in/faculty/sebastiancp/startup/breathe-applied-sciences-pvt-ltd, methanol carbon conversion india startup

1.4 Large Enterprises

#	Company name	Main location(s)	Description of CCUS capability	Key CCUS activity areas: Capture	Utilisation	Transport	Storage	TRL	Website	Search terms and Source of data
1	Tuticorin Alkali Chemicals	Tuticorin	The firm is now using the CO2 from its own boiler to make baking soda – a base chemical with a wide range of uses including glass manufacture, sweeteners, detergents and paper products	x	x			9	https://www.tacfert.in/	https://www.theguardian.com/environment/2017/jan/03/indian-firm-carbon-capture-breakthrough-carbonclean
2	NALCO	Tamil Nadu	Pilot - Carbon Sequestration	x				5	https://nalcoindia.com/	https://www.ceew.in/sites/default/files/ceew-study-on-the-role-of-carbon-capture-utilization-and-storage-in-india.pdf
3	NETRA NTPC	Noida	Involved in 20 TPD CCU pilot plant	x	x			9	https://www.carbonclean.com/media-center/news/ntpc-selects-carbon-clean-and-gpipl-to-set-up-20-tpd-capture-plant	
4	BHEL	Bhubhaneshwar, Angul	Pilot - Carbon Sequestration	x			x	5	https://www.bhel.com/	https://www.ceew.in/sites/default/files/ceew-study-on-the-role-of-carbon-capture-utilization-and-storage-in-india.pdf
5	Dalmia Cement	Kolkata, Ariyalur (TN)	ABPS solvent based capture solution developed along with Carbon Clean (UK)	x	x			9	https://www.dalmiacement.com/	https://www.ceew.in/sites/default/files/ceew-study-on-the-role-of-carbon-capture-utilization-and-storage-in-india.pdf
6	Tata Steel	HQ: Mumbai Installed facility: Jamshedpur	Tata Steel commissioned a 5 t/day carbon capture plant at its Jamshedpur Works, making it the country's first steel company to adopt such a carbon capture technology that extracts CO2 directly from the Blast Furnace gas	x				9	https://www.tatasteel.com/	https://www.tatasteel.com/media/newsroom/press-releases/india/2021/tata-steel-commissions-india-s-first-plant-for-co2-capture-from-blast-furnace-gas-at-jamshedpur/
7	ONGC		Set up a carbon capture plant in Koyali, Tamil Nadu along with crude oil company Indian Oil. It is set up as a pilot, contributing to the overall Enhanced Oil Recovery systems	x	x			5	https://www.ongcindia.com/wps/wcm/connect/en/home	https://www.ceew.in/sites/default/files/ceew-study-on-the-role-of-carbon-capture-utilization-and-storage-in-india.pdf
8	IOCL		CO2 utilization in petrochemical industry, Bio-electrochemical, systems bioremediation microbial corrosion, wastewater treatment, Carbon capture and utilization	x	x				https://ustda.gov/business_opp_oversea/india-feasibility-study-iocl-carbon-capture-and-utilization-project/	
9	Reliance Petrochemicals	Mumbai	Currently exploring various capture technologies. Also evaluating novel catalytic and electrochemical transformations to use CO2 as a feedstock	x	x			1	https://www.ril.com/ourbusinesses/petrochemicals.aspx	https://www.fortuneindia.com/enterprise/ril-bets-on-carbon-capture-to-offset-oil-emissions/105791
10	Hindalco		Evaluating the feasibility of Carbon capture technology. Pilot set for FY23	x				1	http://www.hindalco.com/integrated-annual-report/pdf/natural-capital.pdf	http://www.hindalco.com/upload/pdf/hindalco-q1fy22-investor-presentation.pdf

1.5 Projects

#	Project name	Main location(s)	Leading participants	Description of project	Capture	Utilisation	Transport & Storage	Project status	Year	Final Investment Decision date (if known)	Website
1	Pilot- Carbon Sequestration	Tamil Nadu	NALCO	CCS pilot in its Captive Power Plant at Angul using microalgae to capture CO2	x	x		Completed	2014		https://m.economictimes.com/industry/indl-goods/svs/steel/nalco-to-set-up-pilot-project-on-carbon-sequestration-in-its-cpp/articleshow/7754977.cms
2	Carbon Capture for Enhanced Oil Recovery	Koyali, Gujarat	ONGC IOCL Dastur	Techno-economic feasibility of the Indian Oil Corporation Ltd's (IOC) Carbon Capture and Utilisation Project at the 13.7 Mt/y Koyali refinery in Gujarat	x	x	x	Completed	2022		https://www.thehindubusinessline.com/companies/dastur-completes-feasibility-study-of-carbon-capture-and-utilization-project-at-ioc-koyali-refinery/article65241177.ece
3	Amine-based capture plant for the Cement Industry	Ariyalur, Tamil Nadu	Dalmia Cement	ABPS solvent based capture solution developed along with Carbon Clean for Carbon Capture plant	x			Ongoing	2019		https://www.carbonclean.com/media-center/news/article/2019/09/dalmia-cement-and-ccsl-sign-mou
4	Amine-based capture pilot for the Steel Industry	Jamshedpur, Jharkhand	Tata Steel	Tata Steel commissioned a carbon capture plant at its Jamshedpur Works, to adopt amine based carbon capture technology with Carbon Clean that extracts CO2 directly from the Blast Furnace gas	x			Completed	2021		https://www.tatasteel.com/media/newsroom/press-releases/india/2021/tata-steel-commissions-india-s-first-plant-for-co2-capture-from-blast-furnace-gas-at-jamshedpur/
5	NETRA CCU Pilot Project	Noida	NTPC Carbon Clean Green Power IIT Bombay	Pilot project to capture CO2CO2 to convert to methanol, urea	x	x		Ongoing	2022		https://www.carbonclean.com/media-center/news/ntpc-selects-carbon-clean-and-gpipl-to-set-up-20-tpd-capture-plant

1.6 Technologies

#	Technology Type	Technology name	Leading participants	Description of technology	TRL	Website	Search terms and Source of data
1	Carbon Capture	Fluor Eco amine FG technology	IFFCO, Mitsubishi	Eco amine FG is an amine-based technology for large-scale, post-combustion CO2 capture	9	http://www.zeroco2.no/projects/aonla-urea-plant-india.-indian-farmers-fertiliser-co-operative-ltd	Amine based technology , Post combustion capture in India , CCUS technologies in India
2	Carbon Capture	Amine-Promoted Buffer Salts (APBS) based Solvents	Carbon Clean , Tuticorin Alkali Chemicals and Fertilizers LTD	The solvent can be paired with our CDRMax® process, or used as a drop-replacement for alternative solvents such as MDEA for low pressure gas separations. CDRMax produces CO2 with a purity of 95–99.9% and offers a $40/t cost of capture when used with our CDRMax process. APBS-CDRMax® has high solvent stability, low corrosivity, low regeneration energy requirements, and holds up well in oxygenated environments	9	https://www.carbonclean.com/solvents	Carbon capture technology in Indian Industry, Source is
4	Carbon Capture	Adsorption	Carbon Clean, Tata Steel, TAKL, Dalmiya Cement, NTPC	Polymer based materials like hyper-cross linked polymers (HCPs), covalent organic frameworks (COFs), conjugated microporous polymers (CMPs) and covalent triazine-based frameworks (CTFs) for carbon capture	8	https://timesofindia.indiatimes.com/city/pune/new-compound-that-limits-carbon-footprint-invented/articleshow/88461374.cms	adsorption technologiex,
5	Carbon Capture	IGCC	NTPC	An integrated gasification combined cycle (IGCC) is a technology using a high pressure gasifier to turn coal and other carbon based fuels into pressurized gas—synthesis gas (syngas)	8	https://www.electricityforum.com/news-archive/oct09/IndiadevelopingIGCCplant	IGCC , NTPC and CCUS,
6	Carbon Capture	Oxycombustion	IOCL	Involves the process of burning the fuel with nearly pure oxygen instead of air	8	https://www.researchgate.net/publication/358570137_The_development_of_carbon_capture_and_storage_CCS_in_India_A_critical_review	Oxycombustion in India, IOCL , Oxycombustion projects in India
7	Carbon Capture	Ionic Liquids	BHEL	Ionic liquids, which are salts that exist as liquids near room temperature, are polar, nonvolatile materials that have been considered for many applications	5	https://www.researchgate.net/publicatio	Ionic Liquids technoilogy in India, BHEL CCUS technologies
8	Carbon Capture	Chemical Looping	IICT,	The Chemical Looping Combustion (CLC) concept is based on the transfer of oxygen from the combustion air to the fuel by means of an oxygen carrier in the form of a metal oxide, avoiding the direct contact between fuel and air	4	https://dst.gov.in/new-materials-processes-carbon-capture-and-utilization-could-show-new-light-global-warming-challenge	chemical looping, carbon capture technologies in India
9	Carbon Capture	Calcite looping	IOCL	Calcium looping (CaL) technology – also known as the regenerative carbon cycle (RCC) – removes carbon dioxide (CO_2) from the flue gases of a cement plant (and other power and industrial facilities) using a calcium oxide (CaO) sorbent	3	https://onlinelibrary.wiley.com/doi/abs/10.1002/er.7212	calcium looping technology in India

10	Carbon Capture	Direct Air Capture	Novoclime	Direct air capture (DAC) is a process of capturing carbon dioxide (CO_2) directly from the ambient air (as opposed to capturing from point sources, such as a cement factory or biomass power plant) and generating a concentrated stream of CO_2 for sequestration or utilization	3	https://www.novonanmek.com/	Direct air capture in India, Carbon sequestration in india, Advanced technology in CCUS in India
13	Carbon Capture	Polymer Membranes	IOCL, OIL	Polymeric membranes with composite structure (polymeric composite membrane) offer a better performance in CO2 capturing process than other membranes, due to the composite structure it offers higher gas flux and less material usage, thus facile to use high performed expensive material for membrane fabrication and achieved good efficacy in CO2 capture	9	https://pubmed.ncbi.nlm.nih.gov/35275372/	Polymeric membranes, membrane technology , carbon capture technology in India
14	Carbon Utilisation	Enhanced oil recovery	ONGC	CO2 EOR is a technique used to recover oil, typically from mature fields that have ceased being productive through traditional primary and secondary recovery methods	9	https://www.ongcindia.com/wps/wcm/connect/en/media/press-release/ongc-join-hands-oil-recovery	EOR in India, ONGC and CCUS, ONGC and EOR
15	Carbon Utilisation	Enhanced coalbed methane recovery	TATA , Jharia coal mines	Enhanced coalbed methane recovery (ECBM) involves gas injection into coal to improve methane recovery. CO2 injected into a bituminous coal bed would occupy pore space and also adsorb onto the carbon in the coal at approximately twice the rate of methane, allowing for potential enhanced gas recovery	6	https://www.sciencedirect.com/science/article/abs/pii/S0920410521001571	Enhanced coalbed methane recovery in India, ECMB, TTA
16	Carbon Utilisation	Algae fixation	BITS Pilani, ONGC , BHU	The CO2 sequestration by microalgae can sequester CO2 naturally into O2 and organic matter through the photosynthesis process. The CO2 sequestration by microalgae is considered to be a sustainable alternative approach as it can sequester CO2 naturally into O2 and organic matter through the photosynthesis process	8	https://www.researchgate.net/publication/299520338_Pilot_project_at_Hazira_India_for_capture_of_carbon_dioxide_and_its_biofixation_using_microalgae	Algae fixation in India, Algae sequestration , carbon capture and biofixation
17	Carbon Utilisation	Chemicals conversion to methanol	NTPC, Carbon Clean	The catalytic hydrogenation of CO2 with H2 is used in methanol production	6	https://www.carbonclean.com/media-center/news/ntpc-selects-carbon-clean-and-gpipl-to-set-up-20-tpd-capture-plant	CO2 to Methanol, Methanol and CCUS
18	Carbon Utilisation	Chemical conversion to DME	CIL, MoC,	The catalytic hydrogenation of CO2 with H2 is used in DME production	4	https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1802237	CO2 to DME in India, CCUS Utilization in India
19	Storage	Depleted oil and gas reservoir	IIT Bombay. ONGC	Storage of Captured CO2 in depleted oil and gas wells, making use of storage capacity	4	https://www.sciencedirect.com/science/a	Carbon storage in oil and gas reservoirs
20	Storage	Saline Aquifer	IIT Bombay, NGRI, Monash university	Storage in saline aquifers	2	https://www.sciencedirect.com/science/a	Carbon storage in saline aquifers in India
21	Storage	Mineral Storage	NIT, NGRI	Storage through mineralisation within favourable geological systems	3	https://www.sciencedirect.com/science/a	Mineralization and carbon storage in India

1.7 Policy and Regulation

#	Policy or regulatory instrument name	Owning/administering organisation name	Description of policy or regulatory instrument	Year	Website	Search terms and Source of data
1	Indian Petroleum Act, 1934:	Government of India	Rules for production and transportation of petroleum products. It can be applied for transportation of compressed CO2	1934	https://legislative.gov.in/sites/default/files/A1934-30_0.pdf	Oil and Gas policies for carbon
2	The Petroleum Mineral Pipelines (Acquisition of Right of User in Land) Act, 1962	Government of India	Provides for the acquisition of user in land for laying pipelines for the transport of petroleum and minerals and for matters connected therewith. This law may be applied for transportation of compressed CO2 to storage sites	1962	https://legislative.gov.in/sites/default/files/A1962-50_0.pdf	Policies of carbon in India
3	National Statement by Prime Minister Shri Narendra Modi at COP26 Summit in Glasgow	Government of India	At the 26th Conference of Parties (CoP26), Indian Prime Minister Narendra Modi declared a five-fold strategy — termed as the panchamrita — to achieve this feat. These five points include: - India will get its non-fossil energy capacity to 500 GW by 2030 - India will meet 50 % of its energy requirements from renewable energy by 2030 - India will reduce the total projected carbon emissions by one billion tonnes from now onwards till 2030 - By 2030, India will reduce the carbon intensity of its economy by less than 45 % So, by the year 2070, India will achieve the target of Net Zero	2021	https://pib.gov.in/PressReleseDetail.aspx?PRID=1768712	

4	National Action Plan on Climate Change (NAPCC)	Ministry of Environment, Forest and Climate Change	The plan outlines a national strategy that aims to enable the country to adapt to climate change and enhance the ecological sustainability of India's development path. It stresses that maintaining a high growth rate is essential for increasing living standards of the vast majority of people of India and reducing their vulnerability to the impacts of climate change. Notable points on carbon: - National Mission for Green India: Greening is meant to enhance ecosystem services such as carbon sequestration and storage (in forests and other ecosystems) Enhancing carbon sinks in sustainably managed forests and other ecosystems	2008	https://static.pib.gov.in/WriteReadData/specificdocs/documents/2021/dec/doc202112101.pdf	Indian Strategy on Carbon capture, storage and utilization , Environmental policy on CCUS
5	Policy Framework to Promote and Incentivize Enhanced Recovery Methods for Oil and Gas	Ministry of Petroleum & Natural Gas	The policy will apply to all oil and gas fields across all contractual regimes and nomination acreages with National Oil Companies 10 year policy to screen fields for Enhanced Recovery	2018	http://petroleum.nic.in/sites/default/files/policyeng.pdf	Policy for EOR in India

6	Accelerating CCS Technologies	Multiple countries including India and UK	ACT is an international initiative to establish CO2 capture, utilisation and storage (CCUS) as a tool to combat global warming. ACT means Accelerating CCS Technologies, and the ambition of the 16 partners is to fund research and innovation projects that can lead to safe and cost-effective CCUS technology. The first ACT Call for project proposals was published in 2016 and resulted in eight projects that were started autumn 2017. The second ACT Call was published 2018. The budget for the call was € 31 M and 12 new projects started autumn 2019. The third ACT Call was published in 2020. The budget for the call is € 27M and 12 new projects are planned to commence in autumn 2021	2018	http://www.act-ccs.eu/	Policies for CCUS in India
7	Third Biennial Update Report to The United Nations Framework Convention on Climate Change	Ministry of Environment, Forest and Climate Change	The report embodies information on national circumstances, national GHG inventory, mitigation actions, and an analysis of the constraints, gaps, and related finance, technology and capacity building needs, including information on domestic measurement, reporting and verification (MRV) which includes the status of CCUS in India	2021	https://unfccc.int/sites/default/files/resource/INDIA_%20BUR-3_20.02.2021_High.pdf	Biennial update india, CCUS

8	Mission Innovation IC3	Lead: UK Participant: India	Launched in 2018 Mission Innovation will need to identify what can be done differently to accelerate CCUS. Technologies will need to be developed, tested, and vetted in collaborative forums, building on past experiences and improving on current efforts to further reduce costs.	2018	http://mission-innovation.net/our-work/innovation-challenges/carbon-capture/	CCUS policy and advocacy in India
9	India to have two National Centres of Excellence in Carbon Capture & Utilization at IIT Bombay & JNCASR, Bengaluru, supported by DST	PIB, DST	Two National Centres of Excellence in Carbon Capture and Utilization are being established in India. The two Centres, namely the National Centre of Excellence in Carbon Capture and Utilization (NCoE-CCU) at Indian Institute of Technology (IIT) Bombay, Mumbai and the National Centre in Carbon Capture and Utilization (NCCCU) at Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR), Bengaluru are being set up with support from the Department of Science & Technology, Govt. of India	2022	https://pib.gov.in/PressReleasePage.aspx?PRID=1797178	national strategy on CCUS India

1.8 TEA and LCA

#	Title of leading TEA and LCA CCUS publications	Lead author	Year	Summary of abstract	Weblink to document	Search terms and Source of data
1	Cost implications of Carbon Capture and Storage for the Coal Power Plants in India	Anand B. Rao, Piyush Kumar	2014	CCS is the process of extraction of CO2 from industrial and energy related sources, transport to storage locations and long-term isolation from the atmosphere. It is being considered as a bridging technology, with significant carbon mitigation potential, especially for large point sources such as coal power plants. it would be worthwhile to investigate the necessary and sufficient conditions under which the Indian power plants could graduate to the CCS technologies	https://www.sciencedirect.com/science/article/pii/S187661021401162X#:~:text=The%20values%20of%20incremental%20COE,rate%20of%20the%20base%20plant.	Cost analysis of CCUS in India
2	Techno-economic analysis of Carbon Mitigation Options for Existing Coal-fired Power Plants in India	Udayan Singh, Anand B Rao	2016	India's developmental needs in the near and long-term future will be strongly interlinked with the need to provide steady electricity to its cities and villages. The current fleet of Electricity Generating Units (EGUs) in India is mostly coal-based. There is a strong incentive for repowering of old plants to supercritical units and their subsequent retrofitting with CO2 capture systems than direct retrofitting of low performance plants	https://www.researchgate.net/publication/311483991_Techno-Economic_Assessment_of_Carbon_Mitigation_Options_for_Existing_Coal-fired_Power_Plants_in_India	techno economic study of Carbon capture , TEA on CCUS in India , carbon mitigation, cost of electricity in India
3	An improved tri-reforming based methanol production process for enhanced CO2 valorisation	Abhishek Dwivedi, Ravindra Gudi, Pratim Biswas	2017	The main contributions of this paper to the tri-reforming coupled methanol production process are: (i) proposition of a high pressure tri-reforming step to limit capital costs of the process (ii) establishment of steam input coupled with water separation step as a process improvement whose impact is shown to further amplify at higher tri-reformer pressures. The paper evaluates the process in terms of the profit generating and CO2 valorisation potential of the process as reflected by two parameters, gross margin (GM) and NPCV (net percentage of CO2 valorised) respectively	https://www.sciencedirect.com/science/article/abs/pii/S0360319917330021	CO2 valorization, Methanol production
4	Economic Implications of CO2 Capture from the Existing as well as proposed coal-fired power plants in India under various policy scenarios	Udayan Singh, Anand B Rao, Munish K. Chandel	2017	The paper assesses the economic implications of this technology on existing Indian coal-fired power plants. Some characteristic features of Indian power plants are identified with special reference towards CCS deployment	https://www.sciencedirect.com/science/article/pii/S1876610217320994	Carbon mitigation, clean coal technology, Economic implications of CCUS

5	Relevance of Carbon Capture & Sequestration in India's Energy Mix to achieve the reduction in emission intensity by 2030 as per INDCs	A.R. Akash, Anand B. Rao, Munish K. Chandel	2017	The main objective of this work is to understand the potential role of Carbon Capture & Sequestration (CCS) in coal based power sources in order to meet the committed reduction in the emission intensity (INDC) by the year 2030. The analysis has been carried out under several scenarios characterized by assumptions regarding the GDP growth rate, the energy mix and carbon price. The results indicate that India can meet the INDC by 2030 without deploying CCS in the coal power plants under most of the scenarios	https://www.sciencedirect.com/science/article/pii/S1876610217320854	Emissions, INDC, power and CCUS, carbon sequestration
6	Carbon capture and sequestration potential in India: A comprehensive review	Abhishek Gupta	2018	India's current and expected future emissions are sufficiently massive to have an adverse effect on global mitigation efforts. The IPCC studied that without CCS, the price of achieving long-run climate goals is almost 140% more expensive. However, India has been taking a cautious approach towards CCS technology due to various factors. The paper discusses on the challenges of CCS in India and a roadmap for the successful implementation	https://www.researchgate.net/publication/331695105_Carbon_capture_and_sequestration_potential_in_India_A_comprehensive_review	CCUS in India, carbon emission in India, Carbon sequestration in India

7	Oxy-fuel combustion based enhancement of the tri-reforming coupled methanol production process for CO2 valorisation	Abhishek Dwivedi, Ravindra Gudi, Pratim Biswas	2018	The main contributions of this paper are therefore (i) the proposition of combining oxy-fuel combustion with the tri-reforming coupled methanol production process to mitigate the above drawback, and (ii) utilization of water electrolysis as a source of oxygen and an evaluation of the impact of the generated hydrogen on the CO2 valorisation potential of the process. These two propositions have been implemented as process improvements on the conventional tri-reforming coupled methanol process. The resultant processes have been simulated using Aspen Plus V8.4, optimized and compared in this paper to justify their efficacy	https://www.sciencedirect.com/science/article/abs/pii/S2212982017306224	Oxyfuel combustion in India, CO2 utilization
8	Techno-economic analysis of a 660 MWe supercritical coal power plant in India retrofitted with calcium looping (CaL) based CO2 capture system	Srinath Haran	2021	The publication covers: Technoeconomic study of calcium looping (CaL) retrofitted to Indian coal powerplant. Comparison of CaL for different fuels in calciner and with MEA and Oxycombustion. Lowest LCOE obtained for Indian high ash coal, net negative emissions for biomass. Net power output of CaL system 94 and 81% more as compared to MEA and Oxycombustion. For same net power output, performance of CaL better than MEA and Oxycombustion	https://www.sciencedirect.com/science/article/abs/pii/S1750583621002735	Indian Coal , Chemical looping technology in India , CCUS technology in India
9	Evaluation of Techno-Economic Viability of Carbon Capture Utilization and Storage (CCU&S) with Carbon Credits for Steel Plants	Arunava Maity	2021	The steel sector is actively pursuing the development and adoption of carbon-lean technologies, among which CCUS plays a key role. Since the sources of direct CO2 emissions in the iron and steel sector are very site-specific and dependent on the iron making process, CCU&S in the steel industry faces a greater challenge with respect to choice of technology, process efficiency, total cost incurred and scale up for industrial applications	http://www.dastur.com/CCUS.aspx	CCUS and steel industry, Carbon sequestration , technoeconomic feasibility of CCUS in India

2.1 Research Projects

#	Project name	Technology name	Leading participants	Description of project	Capture	Utilization	Storage	Transport	TRL	Year	Website	Search terms and Source of data
1	Hierarchical porous covalent organic nanosheets and nanosheet –based hybrid membranes for carbon capture and of CO2 Separation	Capture	Dr. Rahul Banerjee, Indian Institute of Science Education and Research Kolkata, Pune	Discovery nanoparticles including covalent organic frameworks zeolites for capturing carbon in their micro and mesoporous voids. These newly designed zeolites could be excellent for CO2 storage in the industry due to their increased chemical stability and high surface area	x				4	TBD	https://www.iiserpune.ac.in/ https://www.iiserkol.ac.in/	https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf
2	Development of methods for Utilisation and conversion of Waste Co2 to Fuels	Utilization	Nandini Devi, CSIR-National Chemical Laboratory, Pune	Various methods of Utilisation and conversion were studied	x	x			3	TBD	https://www.ncl-india.org/	https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf
3	Demonstration of 10,000 l/day syngas generation	Utilization	Ankur Bodoia, CSIR-Indian Institute of Petroleum, Dehradun	Fischer–Tropsch process for the generating synthetic liquid fuels and chemicals from biomass derived synthetic gas	x	x			3	TBD	https://www.iip.res.in/?lang=en	https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf
4	Development of Integrated technologies for reduction of anthropogenic / industrial waste CO2 to value added Chemicals and Fuels	Utilization	Sebastian C. Peter Jawaharlal Nehru Centre for Advanced Science Research (JNCASR), Bangalore, India.	The project team from JNCASR has developed an efficient, cost effective and chemical stable catalyst at pilot-scale for CO2 reduction reaction. Pilot scale plant of 30 kg CO2/day capacity to methanol was operated successfully for a continuous period of 40 days at the time of testing	x	x			4	TBD	https://www.jncasr.ac.in/home	https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf
5	A systematic large scale assessment for potential of CO2 enhanced oil and natural gas recovery in key sedimentary basins in India	Storage	Vikram Vishal, IIT Bombay	Systematic Mapping of the potential carbon storage sites in Indian Geological formations				x	4	TBD	https://www.iitb.ac.in/	https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf
6	Development of hierarchical catalyst for one pot conversion of CO2 rich synthesis gas to Dimethyl ether and scale-up studies	Utilization	Prof. Kamal Kishore pant, Indian Institute of Technology, New Delhi.	The team has successfully developed a novel and economic catalyst for higher conversion levels of syngas rich in CO2. A pressure swing adsorption column has been successfully designed and developed in-house for CO2 capture studies		x			3	TBD	https://home.iitd.ac.in/	https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf
7	Adsorption and separation of CO2 by porous carbon obtained from agro-residues and advanced micro porous materials through cost effective, clean energy methodology	capture	Subarna Maiti, CSIR –Central salt & Marine Chemicals Research Institute, Bhavnagar	Research on recent significant advances in porous carbon materials for CO2 adsorption and separation. Derived from agro-residues and micro porous materials .Strategies to increase the CO2 capture capability are highlighted	x				3	TBD	https://www.csmcri.res.in/	https://www.sciencedirect.com/science/article/abs/pii/S2212982022000944
8	Integrated CO2 absorption and conversion to methanol in slurry phase reactors using metal complexes as catalyst	Utilization	Dr. Sreedevi Upadhyayula Professor, Department of Chemical Engineering, Indian Institute of technology Delhi	Thermocatalytic CO2 hydrogenation to CH3OH via heterogeneous catalysis was used for integrated CO2 absorption and conversion to methanol		x			3	TBD	https://home.iitd.ac.in/	https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf

9	Development of hybrid multi electrode plasma reactor for energy efficient dry reforming of greenhouse gases	Capture	Yugeswaran Subramaniam Pondicherry University (Central University), Pondicherry	The project designed multi electrode plasma reactor for reforming of CH_4. CH_4 and CO_2 were converted to syngas (i.e., H_2 and CO) in a nanosecond pulsed dielectric barrier discharge plasma at a total gas flow rate of 50 sccm	x				4	TBD	https://www.pondiuni.edu.in/	https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf
10	Structure, Interaction and process for energy efficient CO2 separation using Noval Ionic Liquids Supported Membranes	Capture	Swapnil Dharaskar Pandit Deendayal Energy University , Gujarat	The research studied characterization of IL catalysts by spectroscopic techniques, catalytic reactions over catalysts, separation science and technology of ionic liquids, applications in biomass utilization, and synthesis of fine chemicals	x				3	TBD	https://pdpu.ac.in/	https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf
11	Study on new green CO2-capturing solvents	Capture	Dr. Prakash D. Vaidya Institute of Chemical Technology, Mumbai	Greener solvents, such as ionic liquids, amino acid–functionalized ionic liquids, ionic liquid–mixed solvents, and eutectic solvents, have been proposed as promising materials for carbon capture	x				2	TBD	https://www.ictmumbai.edu.in/	https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf
12	Model based design, synthesis and evaluation of Combined Sorbent Catalyst Material (CSCM) for CO2 Capture	Capture	Dr. Yarasi Soujanya CSIR-Indian Institute of Chemical Technology, Hyderabad	The team has designed a dual, fixed cum fluidized bed reactor system based on theoretical calculations along with some preliminary experimental studies. This reactor will be used for testing the new dual functional materials with combined catalytic activity and carbon capture synthesized for SESMR application.					4	TBD	https://www.csir.res.in/indian-institute-chemical-technology-hyderabad	https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf
13	Nano engineered inorganic halide perovskites for Photo, Electro and Thermochemical (PETC) CO2 reduction: Novel artificial photosynthesis implementation for clean energy generation	Capture	Dr. Shravanti S Joshi, Marathwada Institute of Technology (MIT-E), Aurangabad, Maharashtra	Novel concept development for CO_2 reduction using nanoparticles	x				3	TBD	https://engg.mit.asia/	https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf
14	Development of catalysts and a prototype device for conversion of CO2 to fuels / chemicals	Utilization	Arindam Sarkar, Indian Institute of Technology, Bombay	Designed a prototype device using catalysts to convert CO_2 into chemicals	x	x			3	TBD	https://www.iitb.ac.in/	https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf
15	Development of low cost, efficient and scalable materials for CO2 captures using naturally available nontoxic stable materials and industrial solid wastes	Capture	Chinmay Ghoroi, Indian Institute of Technology Gandhinagar, Gandhinagar	Developing low cost materials for capture from industrial solid wastes					3	TBD	https://iitgn.ac.in/	https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf

16	Studies on CO fuels self- sustaining Unmixed Combustion (UMC) reactor for integrated CO2 capture and power/ Steam generation	Capture	Dr. Srinivas Krishnaswamy, BITS Pilani K K Birla, Goa Campus	The research aimed to design, fabricate and commission a 1 - 3 kW Unmixed Combustion test rig for converting CO to CO2. And also conduct a techno-economic feasibility study using process simulation on an integrated UMC / gasification/power and steam generation cycle (IGCC)	x				4	TBD	https://www.bits-pilani.ac.in/Goa/	https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf
17	Development of a geomechanical model for CO2 injection and methane release through experimental studies of matrix shrinkage / swelling, mechanical properties, and permeability of coals	Storage	Pratik Dutta, Indian Institute of Engineering Science and Technology, Shibpur	The research focused on the coal seam properties related to CO2 adsorption/desorption, coal swelling/shrinkage, diffusion, porosity and permeability changes, thermodynamic/thermochemical process, flue gas injection, etc. Here, the performance analysis of both CO2 storage and ECBM recovery process in coal matrixes is investigated based on the numerical simulation	x	x			3	TBD	https://www.iiests.ac.in/	https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf
18	Bench-scale design and development: Investigation of High-Frequency, High-Intensity ultrasonics for carbon-rich solvent regeneration in solvent-based Post-Combustion CO2 Capture Process (PCCC) for reducing CO2 capture energy demand	Capture	Dr. B. Ambedkar , SSN College Of Engineering, Chennai	Megasonics-assisted (1 MHz - tank-type) solvent regeneration process had been investigated experimentally. The results revealed that low regeneration temperature (<45 °C), less condenser duty, the potential for sensible heat saving, no reboiler is required facilitates capital and maintenance saving, no significant colour change after regeneration and loss of absorption capacity after regeneration was 3.7 times lower than the conventional	x	x			3	TBD	https://www.ssn.edu.in/	https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf
19	Simulation of CO2 enhanced coalbed methane recovery in Jharia coalfields, India	Utilization	Dr Vikram Vishal, IIT Bombay	Long-term feasibility assessment for CO2-ECBM recovery in Jharia coalfield					4			
20	Sensitivity analysis of geomechanical constraints in CO2 storage to screen potential sites in deep saline aquifers	Storage	Vikram Vishal, P. G. Ranjith, Yashvardhan Verma, IIT Bombay, Monash University	The current analysis computes the effect of rock properties (porosity, permeability, permeability anisotropy, pore compressibility, and formation water salinity) and injection rate on both these parameters by simulating CO2 injection at the bottom of a 2D mesh grid with hydrostatic boundary conditions					2			
21	Saturation time dependency of liquid and supercritical CO2 permeability of bituminous coals: Implications of carbon storage	Storage	Vikram Vishal, IIT Bombay	Work examines the effect of various saturation periods on the permeability evolution of porous coal					2			
22	Influence of sorption time in CO2 ECMB process in Indian coals using couple numerical simulation	Utilization	Vikram Vishal, P. G. Ranjith, T.N. Singh , IIT Bombay, Monash University	This study investigates the role of sorption time in the production behaviour of coal under carbon dioxide injection using numerical simulation					4			

23	Numerical modelling of Gondwana coal seams in India as coal bed methane reservoirs as substitute for CO2 sequestration	Utilization	Vikram Vishal, IIT Bombay	The project was initial technical estimate for CO2 driven ECBM (enhanced coalbed methane) at a regional scale in India and establish the technical feasibility of CO2 driven recovery					4			
24	In situ disposal of CO2: liquid and supercritical CO2 permeability in coal at multiple downhole stress condition	Utilization	Vikram Vishal, IIT Bombay	In this study, permeability experiments were approached using the supercritical and liquid phases of CO2 (less understood; most likely insitu phases) for naturally fractured bituminous coal. Experiments were performed under triaxial conditions using four sets of various confinement conditions corresponding to variable depth					3			
25	Experimental investigation of some metal oxides for chemical looping combustion in a fluidized bed reactor	Capture	Munish Chandel, IIT Bombay, A. Hoteit, Ecole des Mines de Nantes, France	In this study, NiO–NiAl2O4, Cu0.95Fe1.05AlO4, and CuO–Cu0.95Fe1.05AlO4 were tested experimentally in a fluidized bed reactor as a function of oxidation–reduction cycles, temperature, bed inventory and superficial gas velocity. The results showed that flue gases with a CO2 concentration as high as 97% can be obtained					2			
26	Suitability of carbon capture technologies for carbon capture and storage in India	Capture	Dharmender Yadav, IIT Roorkie	This work analyses the suitability of various CO2 capture technologies for Indian coal power plants on the basis of different parameters: energy penalty, cost of CO2 capture, efficiency, and age and size of the power plant					2			
27	200 MW chemical looping combustion based thermal power plant for clean power generation	Capture	Raman Sharma, IIT Delhi , Munish Kumar Chandel , Duke University Durham	The present study demonstrates a possible configuration of a 200 MW chemical looping combustion (CLC) system with methane (CH4) as fuel					2			
28	Potential economies of scale in CO2 transport through the use of a trunk pipeline	Transport	Munish Chandel, IIT Bombay, A. Hoteit, Ecole des Mines de Nantes, France	Study of the cost of CO2 transport through trunkline pipeline by developing an engineering-economic model that computes the levelized cost of transporting captured CO2 through pipes of different diameters and over varying distances					2			
29	In situ growth of zeolitic imidazolate framework -67 nanoparticles on polysulfone/ graphene oxide hollow fibre membranes enhance CO2/CH4 separation	Capture	Krishnamurthy Sainath, Akshay Modi, Jayesh Bellare	A novel strategy of in-situ growth of ZIF-67 on hollow fibre membranes demonstrated					2			

2.2 Research Networks

#	Research network name	Main participants	Description of research activity	Website	Search terms and Source of data
1	Accelerating CCS Technologies (ACT)		ACT is a global CCS research funding group, originally designed to run from 2016-21, but has since been extended under ACT3 – including funding from both UK and India, among others. They have funded a wide range of projects	http://www.act-ccs.eu/	
2	European CCUS Research infrastructure ECCSEL ERIC	ECCSEL is the European Research Infrastructure for CO2 Capture, Utilisation, Transport and Storage (CCUS). They are supporting CCS projects in India.	Infrastructure for CO2 CCUS	https://www.eccsel.org/	
3	Asia Pacific Partnership for Clean Development and Climate		The partnership established eight public-private sector Task Forces in cleaner fossil energy, power generation, steel, cement and coal to address energy security and climate change mitigation	https://www.iea.org/policies/4319-asia-pacific-partnership-for-clean-development-and-climate	

Carbon Capture Utilisation and Storage (CCUS) in India and the UK

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