Education

Addressing the CO_2 challenge: the role of carbon capture and sequestration in reinventing climate solutions

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Abstract

Climate change is one of the major causes of global warming and its consequent serious, complex and cascading risks are being felt across different sectors and regions of natural and human systems on all continents and across the oceans. Various complementary strategies in relation to adaptation and mitigation processes are being adopted at local, regional, national and global levels for reducing and managing the greenhouse gas emissions and the risks of climate change, thereby assessing their interaction with sustainable development. In order to address this problem, a revolution in energy technology and the transformation of energy systems are needed that includes higher energy efficiency, increased renewable energies and the decarbonisation of fossil fuel-based power generation. 'Carbon Capture and Sequestration (CCS)' technology is one such prospective mitigation strategy that allows continuous use of fossil fuels and provides time to make the changeover to other energy sources in a systematic way – so as to achieve the large-scale reductions in atmospheric CO2. The technology involves capture, transport and storage of CO2. Developing appropriate policy instruments and support frameworks focusing on carbon pricing are the need of the moment from policymakers and governments so as to aggressively drive negative emissions projects.

Keywords: CCS, Climate change, CO_2, Carbon capture, Carbon storage, Carbon transport, Sequestration

1. Introduction

Climate change refers to long-term shifts in temperatures and weather patterns caused mainly by the emission of greenhouse gas at a global level. Emission of such greenhouse gases (GHGs) like carbon dioxide, methane, nitrous oxide, hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs) and ozone and their trapping in the lower atmospheric level cause heat to be trapped by the earth's atmosphere. This has been the main driving force behind global warming and its resultant serious, complex and cascading risks across different sectors and regions of natural and human systems on all continents and across the oceans (IPCC, 2014a; 2022) [1, 2]. Such emissions may be sourced from both natural systems [like forest fires, earthquakes, oceans, permafrost, wetlands and volcanoes (Yue and Gao, 2018) [3] and human activities [mostly related to energy production, industrial activities and activities related to changes in forestry and land use patterns (IPCC, 2014b) [4]]. Comparing global greenhouse gas emissions from natural systems and anthropogenic activities, Yue and Gao's (2018) [3] statistical analysis concluded that while natural systems on Earth tend to be self-balancing, anthropogenic emissions are, in contrast, placing additional stress on the planet's system at an alarming rate.

Addressing the climate change realities by gathering latest knowledge on climate change and variability caused by natural and human systems and assessing future impacts and risks, the first world climate conference was held in Geneva in 1979. Aiming towards formulating climate-related policies by governments and official bodies, an Intergovernmental Panel on Climate Change (IPCC) was set up by the World Meteorological Organization (WMO) in collaboration with the United Nations Environment Programme (UNEP) in 1988 (WMO, 1979) [5]. The Kyoto protocol - an international treaty, adopted in 1997 at the third UNFCCC conference (COP-3) and enacted in 2005, set greenhouse gas emission reduction commitments for developed countries by an average of 5% below 1990 levels for the period of 2008 to 2012. It emphasized implementation of mechanisms like certified emission reduction unit, assigned amount unit and removal unit to help achieve the set goals (Fawzy et.al., 2020) [6]. However, facing some challenges, the former was effectively replaced by the Paris agreement in 2015.

Various complementary strategies in relation to adaptation and mitigation processes are being adopted at local, regional, national and global levels for reducing and managing the greenhouse gas emissions and subsequent risks of climate change, thereby assessing their interaction with sustainable development (IPCC, 2014a) [1]. Among the various future solutions, one much promising multifaceted approach is the Carbon Capture and Storage (CCS) technology. This is designed conjoining the sustainable development and integrating insights from various disciplines of science, engineering and economics, while actively considering questions of distribution and democratic participation (Jafry *et al*., 2018) [7].

2. Carbon Capture and Storage (CCS): The basics

As fossil fuel consumption is expected to continue to dominate global energy supplies as a main indigenous energy resource (Fig 1), alternative energy sources and technologies are unlikely to completely replace the same in the near future. Thus, the key question remains whether it is possible to speed up the transition to sustainable energy systems based on renewable energy sources like biomass, hydro, nuclear, solar, wind, geothermal and tidal energies (Oh, 2010; Dangerman and Schellnbuber, 2013) [8, 9]. In this situation, the long-term solution of reducing greenhouse gas emissions is to decouple energy consumption from CO_2 emissions. In order to address this problem, a revolution in energy technology and the transformation of energy systems are needed, that includes higher energy efficiency, increased renewable energies and the decarbonisation of fossil fuel-based power generation.

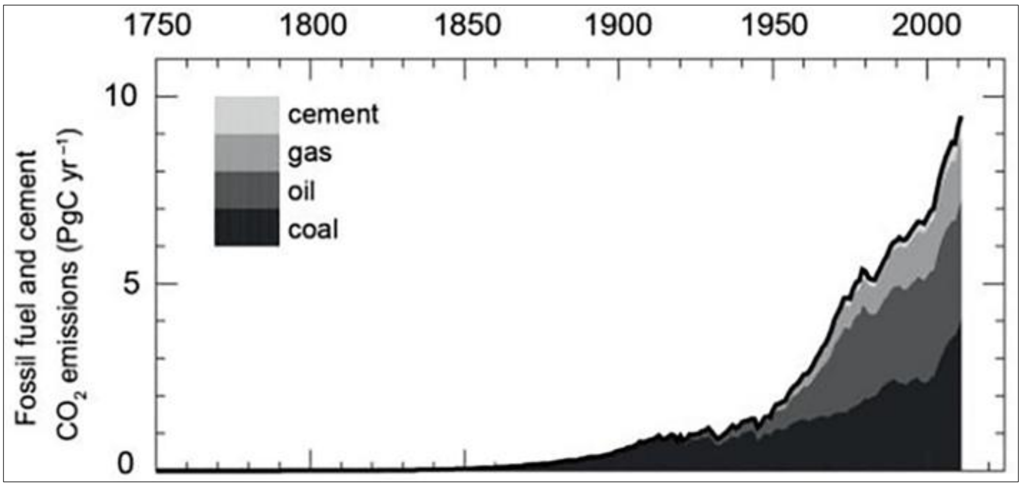

Fig 1: Annual global anthropogenic CO_2 emissions (*PgC/year*) by category from 1750 to 2011, estimated by the Carbon Dioxide Information Analysis Centre (CDIAC) (IPCC, 2013) [10]

In the present days, three climate change mitigation strategies are being explored to act against the increased energy demand by mankind (Fig. 2): a) to increase energy efficiency, b) to switch to less carbon-intensive sources of energy, and c) to capture and sequester carbon (Carbon Capture and Sequestration or CCS). In order to achieve the large-scale reductions in CO_2, CCS technology allows the continuous use of fossil fuels and in a systematic way provides time along with to make the changeover to other energy sources. Such a measure is appearing as a transition until renewable and nuclear energies can replace fossil fuel energy (Surridge and Cloete, 2009) [11]. Therefore, in order to mitigate climate change and initiate sustainable development CCS technology is certainly necessary both at global and national scales.

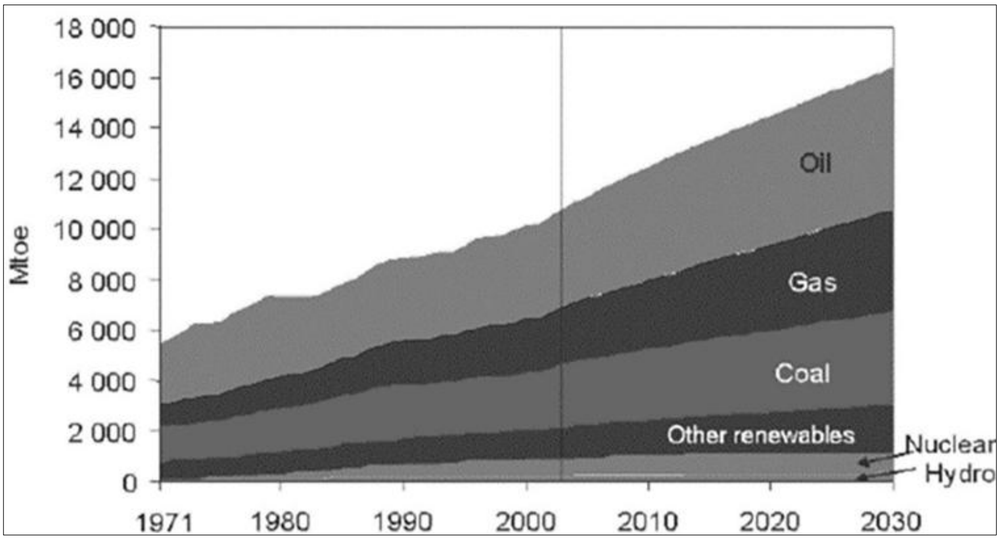

Fig 2: Projected energy demand until 2030 (International Energy Agency, 2005) [12]

Carbon Sequestration, in a popular sense, can be defined as the three-tier process of capturing, transporting and storing the atmospheric CO_2, which occurs both naturally and as a result of anthropogenic activities. The term 'Carbon Capture and Sequestration (CCS)' is defined in a more technical and detailed way by Surampalli et. al. (2015) [13] as any technologies/methods that are to (a) capture, transport and store carbon (CO_2), (b) monitor, verify and account the status/progress of the CCS technologies employed, and (c) advance development/uptake of low-carbon technologies and/or promote beneficial reuse of CO_2 (Table 1) (Fig 3).

The technology of CCS although sounds promising, its applicability however depends on a number of factors worldwide, such as technical development, overall potential, flow and shift of the technology to developing countries and their capability to apply the technology, regulatory aspects, environmental concerns, public perception and costs (Surampalli et. al., 2015) [13]. CCS costs variously depend on the type of process, capture technology, CO_2 transport and storage location.

Current technological solutions available for addressing climate change include improved fuel economy, reduced dependency on automobiles, more efficient buildings, improved power plant efficiency, decarbonisation of electricity and fuels, replacement of natural gas for coal, carbon capture and sequestration (CCS), nuclear fission, wind electricity, photovoltaic electricity, and biofuels (Pacala and Socolow, 2004) [14]. Of all these strategies, CCS is mentioned as a strong option to achieve the large-scale reductions in CO_2 that are required during this century (IPCC, 2005) [15]. Recent analytical studies found that the emissions of CO_2 will be reduced by approximately 350 Mt CO_2/yr by 2030, if CCS is used extensively after 2020 in the US power sector alone (EPRI, 2008) [16].

Table 1: Some of the low-carbon technologies, out of the 124 items listed as a Harmonized System Codes that is included in the definition of Low Carbon Technology (LCT) Products for the IMF Climate Change Indicators Dashboard (IMF, 2021) [17]

Sr. No	Code: HS 2017	Description
1	280519	Alkali or alkali-earth metals; other than sodium and calcium
2	282520	Lithium oxide and hydroxide
3	392010	Plastics; plates, sheets, film, foil and strip (not self-adhesive), of polymers of ethylene, non-cellular and not reinforced, laminated, supported or similarly combined with other materials
4	441873	Wood; assembled flooring panels, of bamboo or with at least the top layer (wear layer) of bamboo
5	730900	Reservoirs, tanks, vats and similar containers; for any material (excluding compressed or liquefied gas), of iron or steel, capacity exceeding 300l, whether or not lined or heat insulated
6	840110	Nuclear reactors
7	841581	Air conditioning machines; containing a motor driven fan, other than window or wall types, incorporating a refrigerating unit and a valve for reversal of the cooling/heat cycle (reversible heat pumps)
8	850650	Cells and batteries; primary, lithium
9	853950	Lamps; light-emitting diode (LED) lamps
10	854140	Photosensitive semiconductor devices, including solar cells
11	860120	Rail locomotives; powered by electric accumulators
12	870220	Vehicles; public transport type (carries 10 or more persons, including driver), with both compression-ignition internal combustion piston engine (diesel or semi-diesel) and electric motor for propulsion, new or used

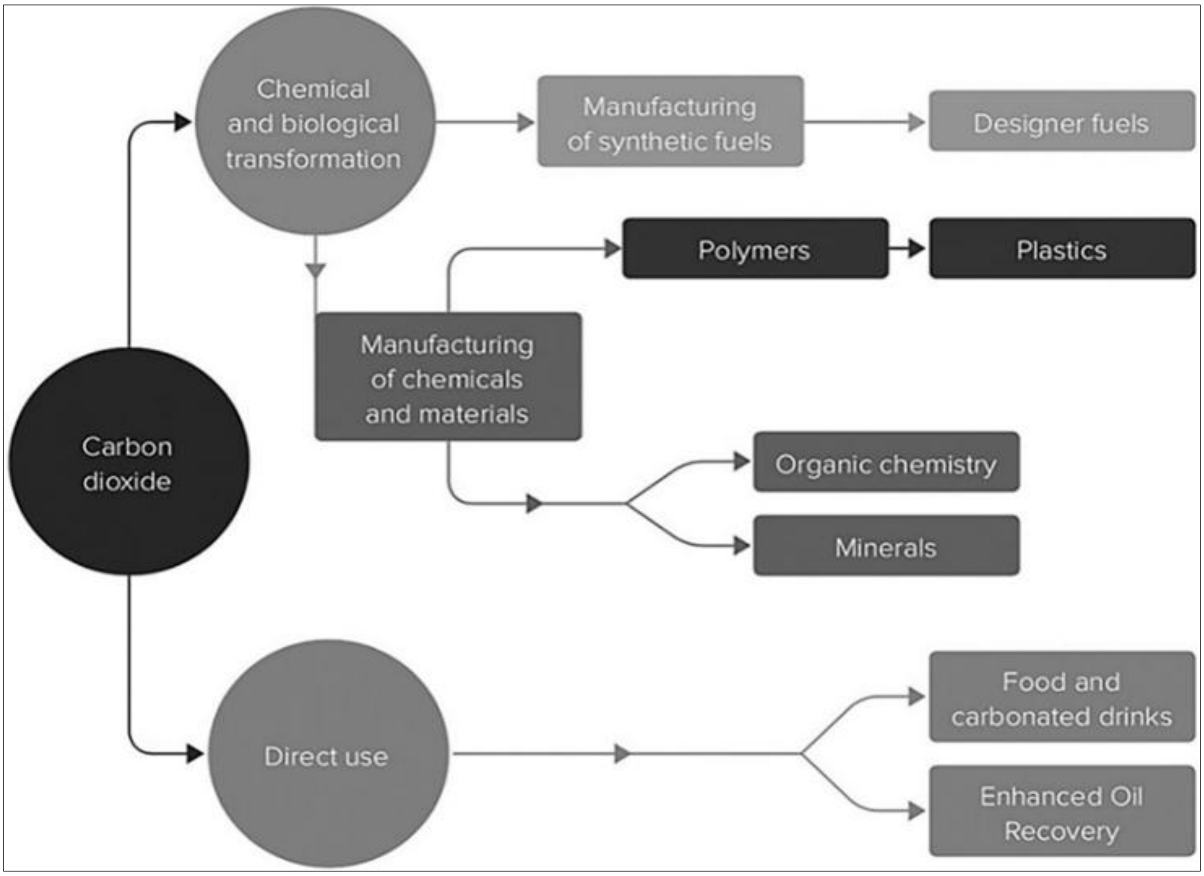

Fig 3: Six Re-Uses of CO_2 (Royal Society, 2017) [18]

3. The technologies involved in CCS

The technology involved in CCS involves capture, transport and storage of CO_2. Each process is detailed out in separate categories.

A. CO_2 capture

According to Zhang and Surampalli (2013) [19], technologies involved in CO_2 capture can be categorized based on whether -

- Carbon capture is from concentrated point sources or from mobile/distributed point- or non-point sources; and
- The technique involves physical/chemical or biological processes.

A brief description of the major technologies is given below:

Category (a).

- Carbon capture from mobile/distributed sources like cars and on-board capture would not be possible at affordable cost, but are still needed.
- Carbon capture from concentrated sources have been applied for very long time by industries using technologies mainly to remove or separate out CO_2 from other gases that are produced in the generation process when fossil fuels are burnt (IEA, 2009) [20]. This can be done in at least three different ways: 'post-combustion', 'pre-combustion' and 'oxy-fuel combustion (Fig. 4).

Post-combustion capture: This involves capturing CO_2 from the exhaust of a combustion process. The different methods for separating CO_2 include high pressure membrane filtration, adsorption, desorption processes and cryogenic separation. Among all these methods, the more established method is solvent scrubbing. Currently, in several facilities, amine solvents are used to capture CO_2 in significant proportions (IEA, 2009) [20]. The absorbed CO_2 is then compressed for transportation and storage.

Pre-combustion capture: In this process, fuel in any form is first converted to a mixture of hydrogen and CO_2 by gasification process and then followed by separation of CO_2 to yield a hydrogen fuel gas. The hydrogen produced in this way may be used for electricity production and also in the future to power our cars and heat our homes with near zero emissions. The pre-combustion capture technology elements have already been proven in various industrial processes other than large power plants (IPCC, 2005) [15].

Oxy-fuel combustion systems: In this process, the recycled flue gas enriched with oxygen (separated from air prior to combustion) is used for combusting the fuel so as to produce a more concentrated CO_2 stream for easier purification. This process confirms high efficiency levels and offers key business opportunities. This method has been demonstrated in the steel manufacturing industry at plants up to 250 MW in capacity (IEA, 2009) [19].

In general, for power generation projects, most studies estimate CO_2 capture will account for up to 75% of the total cost of CCS, measured in cost per tonne stored. Part of this cost is due to the energy required by the capture process itself. Finally, CO_2 can also be captured in restricted quantities from industrial practices that do not involve fuel combustion, such as natural gas purification.

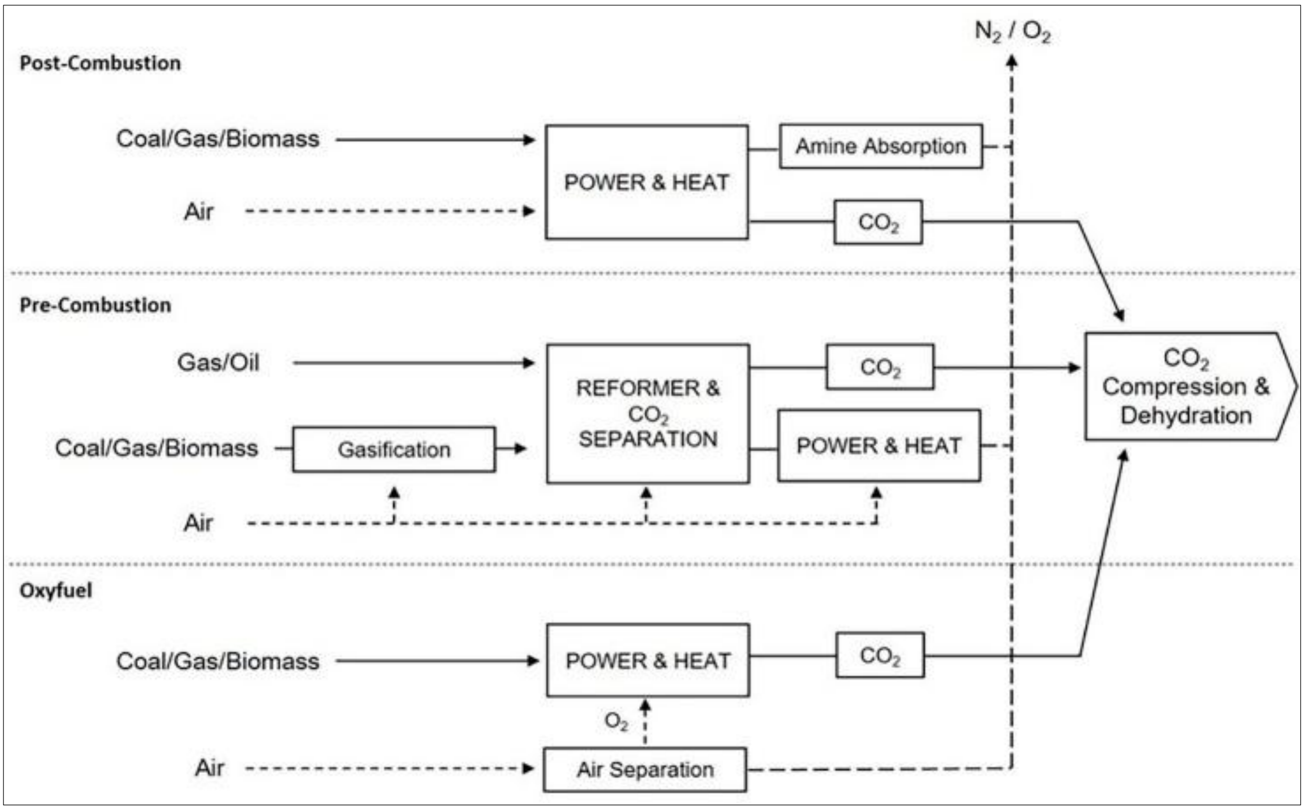

Fig 4: Various types of carbon capture processes from concentrated sources (Modified from Freund and Kårstad, 2007[21]).

Category (b)

Other than the three technologies described in Category (a), sorption and membranes are the two major physical/chemical technologies for carbon capture. There are many biological technologies that can be used for carbon capture from either point or non-point sources, such as i) trees and organisms; ii) ocean flora; iii) biomass-fuelled power plant, biofuels and biochar; and iv) sustainable practices (e.g., soils, grasslands, peat bogs). Biological methods often combine carbon capture and sequestration together (Table 2) (Zhang and Surampulli, 2013) [19].

Table 2: Alternative biological technologies for Carbon Capture/Sequestration (Zhang and Surampulli, 2013) [19]

Methods	Description
Trees/organisms	▪ Capture CO_2 via photosynthesis (e.g. reforestation or avoiding deforestation); cost range 0.03-8\$/t-CO_2; one-time reduction, i.e. once the forest mature, no capture; release CO_2 when decomposed ▪ Develop dedicated biofuel and biosequestration crops (e.g., switchgrass); enhance photosynthetic efficiency by modifying Rubisco genes in plants to increase enzyme activities; choose crops that produce large numbers of phytoliths (microscopic spherical shells of silicon) to store carbon for thousand years.
Ocean flora	▪ Adding key nutrients to a limited area of ocean to culture plankton/algae for capturing CO_2. ▪ Utilize biological/microbial carbon pump (e.g., jelly pump) for CO_2 storage. ▪ Problems/concerns: a) large-scale tests done but with limited success; b) limited by the area of suitable ocean surface; c) may have problems to alter the ocean's chemistry; and d) mechanisms not fully known.
Biomass-fueled power plant, bio-oil and biochar	▪ Growing biomass to capture CO_2 and later captured from the flue gas. Cost range = 41\$/t-CO_2 ▪ By pyrolyzing biomass, about 50% of its carbon becomes charcoal, which can persist in the soil for centuries. Placing biochar in soils also improves water quality, increases soil fertility, raises agricultural productivity and reduce pressure on old growth forests ▪ Pyrolysis can be cost-effective for a combination of sequestration and energy production when the cost of a CO_2 ton reaches \$37 (in 2010, it was \$16.82/ton on the European Climate Exchange).
Sustainable practices, e.g. ▪ Soils/grasslands ▪ Peat bogs	▪ Farming practices (e.g. no-till, residue mulching, cover cropping, crop rotation) and conversion to pastureland with good grazing management would enhance carbon sequestration in soil. ▪ Peat bogs inter ~25% of the carbon stored in land plants and soils. However, flooded forests, peat bogs, and biochar amended soils can be CO_2 sources.
Enzymatic sequestration	▪ CO_2 is transformed, via enzymes as catalysts, into different chemicals, such as i) HCO_3^-/CO_3^{2}, ii) formate, iii) methanol, and iv) methane.

B) CO_2 transport

After capturing the CO_2, it is compressed and purified for efficient transport for storage at a suitable site. Transportation takes place by various means such as pipelines, ships, trucks or trains.

- **Pipeline:** CO_2 is already transported for commercial uses by large as well as safe and reliable networks of CO_2 pipelines. They are the most common, efficient and economical way of transporting large volumes of compressed CO_2 over long distances. Hence local and regional infrastructures of pipelines will eventually be developed in future, with a possibility of re-using certain existing pipeline networks. However, unlike oil and natural gas pipelines, CO_2 pipelines function at much higher pressure. CO_2 pipelines are in operation and operated safely for over 30 years in USA and Canada through 6200 km of pipeline network (IEA, 2009) [20].
- **Road/Rail tankers on land:** In cases, where pipeline technology is becoming expensive, and smaller quantities are to be transported over short distance, rail and road tankers are the best suitable option for CO_2 transportation (IPCC, 2005) [15].
- **Shipping:** This option is possible when the distance between emission source and seaport facilities is adequate to load CO_2 for injection in offshore locations. Such overseas transportation of liquefied natural gas occurs in Norway and Japan (GCCSI, 2009) [22].

However, there are variations related to the issues of short- and long-term cost for setting up such strategies and maintaining them in relation to the source and storage units, as well as the interlinking interface conditions such as pressure, temperature and flow rates of CO_2 while transporting the same.

C) CO_2 storage

Various options are available for CO_2 storage that includes deep saline reservoirs, depleted or declining gas and oil fields, enhanced oil and gas recovery, enhanced coal bed methane, basalt formations and others (GCCSI, 2009) [22]. From the ecological and economic perspectives, storage in geological formations is currently the most attractive option. Some of these methods are briefly described below (Fig. 5).

a) Pure geological storage options

This kind of storage is relatively permanent which means that the CO_2 must not leak back into the atmosphere at any significant rate for hundreds of years. To achieve this kind of permanence of storage, injection of CO_2 must take place at depths in excess of 800 metres so that the gas can be prevented from migrating back to the surface by the help of geological cap rock and other geochemical trapping mechanisms. These kinds of geological formations are found both on- and offshore in various locations around the world. The most suitable geological formations for long-term CO_2 storage are deep saline aquifers and depleted oil and gas reservoirs. The bottom of deep-sea beds is also a possible storage location for CO_2, where the gas can either be injected into the water column for dissolution or injected through pipelines to the deep-sea bed. As liquid CO_2 is denser than sea water, the injected CO_2 would then remain at the bottom of the sea-bed in the form of a "lake" (Bumb and Raj, 2023) [23].

b) Enhanced hydrocarbon recovery: Apart from pure storage, CO_2 can also be used for Enhanced Hydrocarbon Recovery. This includes –

- **Enhanced Oil Recovery (EOR)**: In crude oil extraction, numerous different techniques are used to increase the yield. One of these is the injection of CO_2. After injection of CO_2 into the soil reservoir, there is increase in pressure in the reservoir which diffuses into the crude oil, making it more fluid and therefore easier to extract. Hence, using CO_2 for EOR can ensure an increase in oil yield, and at the same time permanent transfer of the gas into geological formations and its removal from the atmosphere. Enhanced oil recovery through CO_2 injection is already being used at various places across the world (e.g., the Weyburn oil field in Canada) and can be regarded as an established technology.
- **Enhanced Gas Recovery (EGR):** CO_2, owing to be heavier than natural gas, when injected into the base of a depleted gas reservoir will tend to pool there, causing any remaining natural gas to float on top of it - thereby driving the natural gas further towards the production wells. However, the potential target for EGR is small since a high percentage of the natural gas contained in many gas fields can be recovered without using EGRs. As there has been no practical experience with the analogous process of EGR, hence there has only been work on simulations to date (Fischedik *et al*. 2007) [24].
- **Enhanced Coal-bed Methane Recovery (ECBM):** Due to fractures and micro pores in coal beds in which natural gas in the form of coal-bed methane (CBM) can be found adsorbed onto the surface, the coal beds can act as reservoirs for gases. As CO_2 has a greater adsorption affinity onto coal than methane, hence if CO_2 is pumped into a coal bed towards the end of a coal-bed methane production project, it results in displacement of any remaining methane at the adsorption sites, allowing the recovery of methane in conjunction with the storage of CO_2. However, at this point, it has to be remembered that methane being far more potent greenhouse gas than CO_2, therefore, precautionary steps would have to be taken to ensure no methane leakage into the atmosphere. Smaller field trials of ECBM production using CO_2 are in process in Europe, Canada and Japan.

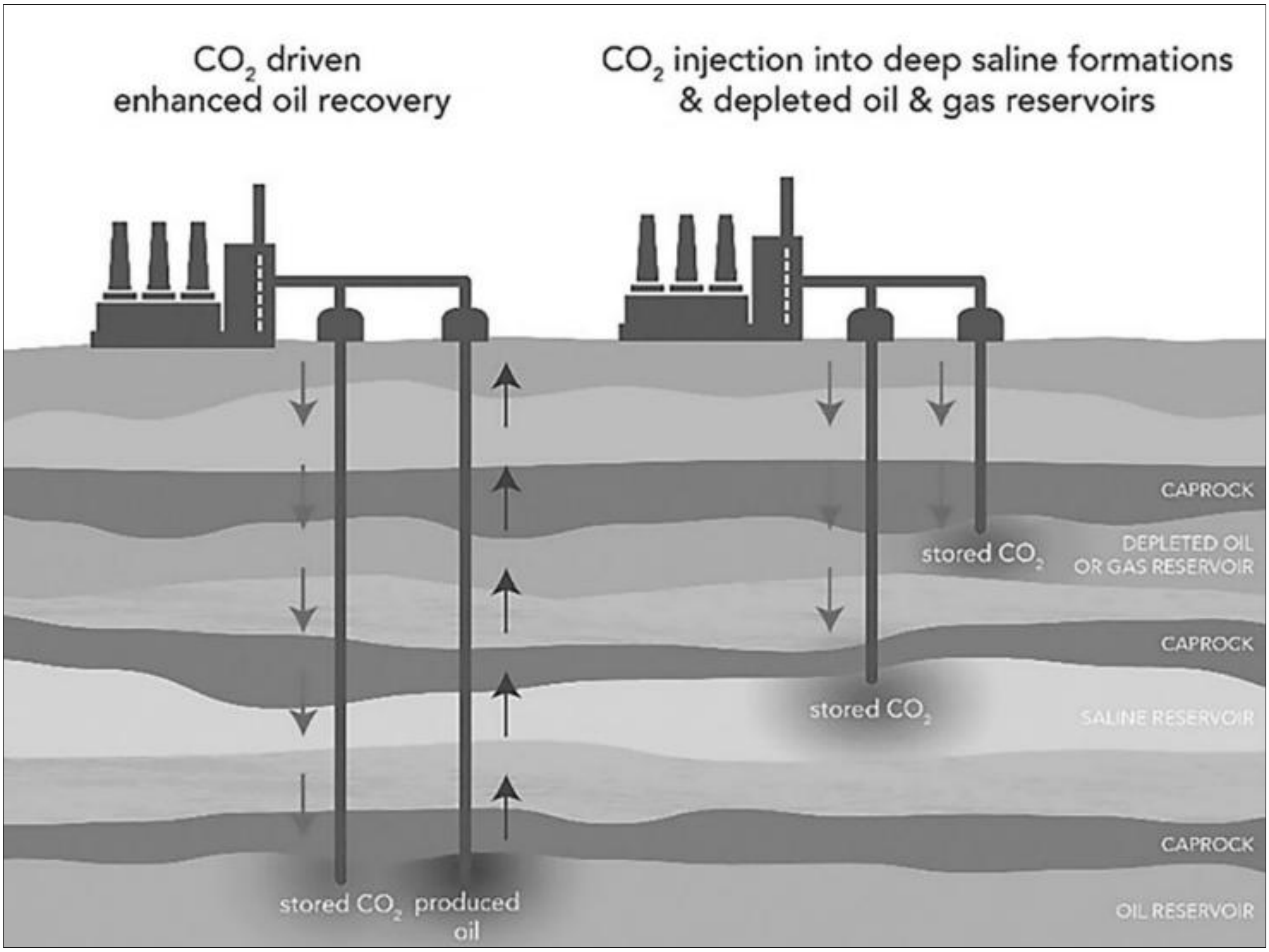

Fig 5: A comparative scheme for the different carbon storage options from North Dakota's first carbon capture and storage project (California Air Resources Board, 2022) [25]

c) Other alternatives

- The idea of binding CO_2 in the marine environment either directly (storage in the ocean depths) or indirectly (e.g., algae formation) is currently being pursued only occasionally (mainly in Japan) due to public opposition (the question of permanence of storage as well as insufficient knowledge of the effects on marine ecosystems) and low efficiency.
- CO_2 can also be fixed through the deliberate cultivation of biomass (e.g. through afforestation and reforestation programmes).
- In the United States of America, processes for binding CO_2 to silicates (mineralisation) are being discussed, but the high energy requirements and large amounts of material to be disposed of are discouraging.

However, successful geological storage of CO_2 follows regular monitoring and security check of the storage sites to mitigate any risk of potential gas leakage, seismic activities, etc.

A flow chart summarizing the CCS technology in a nutshell is provided in Figure 6.

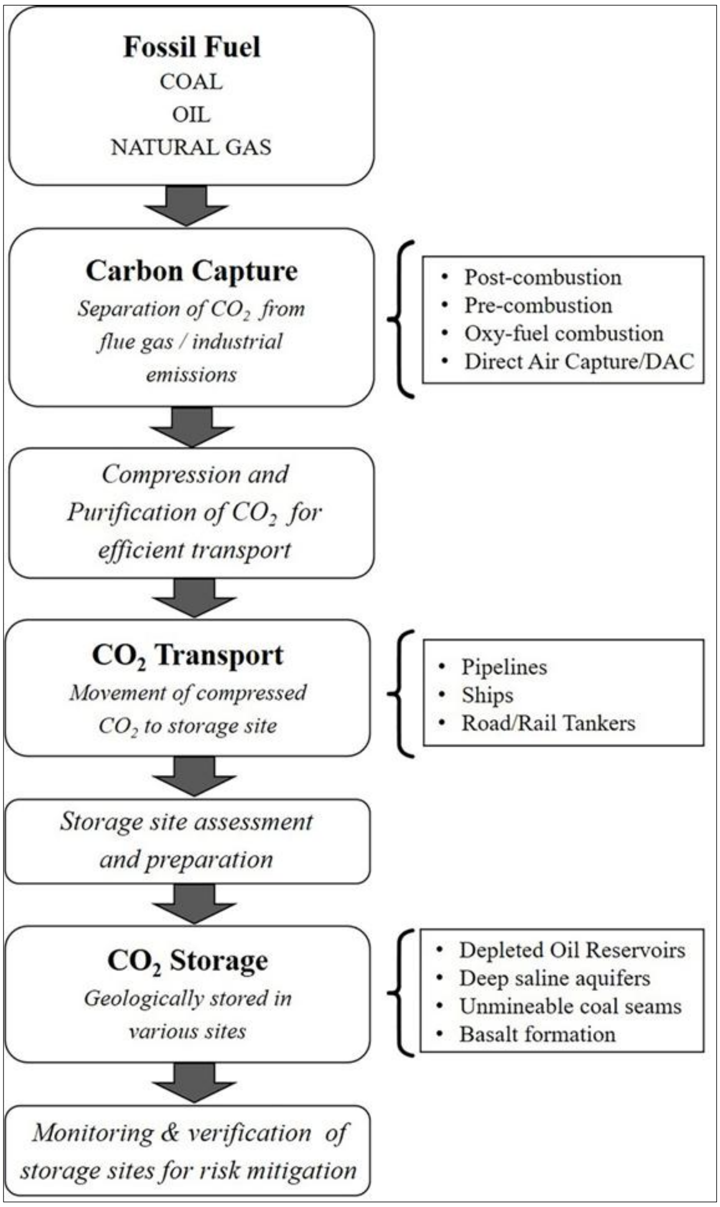

Fig 6: A simplified overview of the technologies involved in Carbon Storage, Transport and Storage (CSS)

4. Conclusion

It is important to note that there occurs no silver bullet towards a single technology or strategy as a measure to curb climate change through CO_2 emission. There is a need towards formulating a comprehensive approach by combining a variety of measures to achieve meaningful reductions in greenhouse gas emissions and carbon sequestration. The factors needed to keep in mind while implementing any biological, physical or chemical technology are – cost, scale of application, environmental impacts and public acceptance. With further research and development, these technologies could become more cost-effective, scalable, and environmentally friendly.

There is an extensive debate regarding contribution of CCS technologies in bringing about long-term deep decarbonisation, although recognising the role CCS could play in climate change initiatives. Currently, although the technology seems economically unviable, long-term analysis across scenarios stress the need for CCS in the energy system (Malyan and

Chaturvedi, 2021) [26]. As India is the global third largest emitter of CO_2 with estimated annual emissions of about 2.6 gigatonne per annum, a magnitude of disruptive transformation will be required in the energy systems to achieve net-zero climate targets across different scenarios by 2050 and reaching net zero by 2070 (Chaturvedi, 2021; Mukherjee and Chatterjee, 2022) [27, 28]. To curb emissions from the industrial sectors and fuel-based power generation, India's decarbonisation pathway has to embrace technologies like CCS along with renewable power generation projects using solar and wind power. However, stakeholders in the country have largely remained sceptical of the CCS technology because of the negligible progress on the deployment of this technology in the last two decades, the perverse incentive it presents to postpone mitigation actions, and the potential increase in the cost of power generation if this technology is deployed. In contrast, CCS offers a lease of life to investors and corporations in fossil-energy-dependent businesses and could save them from massive disruptions required to achieve a low carbon future (Malyan and Chaturvedi, 2021) [26], also ensuring sustainable development and economic growth in India in areas like (i) energy, materials and food security and self-sufficiency, (ii) enabling sectors of coal gasification and low-carbon hydrogen economy and (iii) sustenance of existing emitters like crude steel and coal-based power capacities (Mukherjee and Chatterjee, 2022) [28].

Keeping in mind the current state of climate emergency, there is an urgent need of development of viable mitigation and adaptation mechanisms. Construction of appropriate policy instruments and support frameworks focusing on carbon pricing are the need of the moment from policymakers and governments so as to aggressively drive negative emissions projects. Moreover, an enhanced financial support and accessibility should be provided by the financial industry as well as introducing efficient market-based mechanisms to incentivize project developers to establish carbon removal projects (Fawzy et. al., 2020) [6]. Overcoming the challenges of (i) wasteful allocation of resources and maladaptation and (ii) implication of sustainable development outcomes result from decision-making process (von Stechow *et al*., 2015) [29] as well as significant learning and innovative ways of linking science, practice and policy at all scales (Shaw and Kristjanson, 2014) [30], so as to avoid maladaptation and malmitigation, including climate injustice (Seddon *et al*., 2019; Cousins, 2021) [31, 32].

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