# Carbon capture and storage: an effective way to mitigate global warming

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*Ever since industrialization occurred, there has been an increase in the burning of fossil fuels to meet the high energy demands. The use of such fuels causes emission of carbon dioxide ($CO_2$) and other greenhouse gases which lead to global warming. Such a warming may have a highly injurious impact to life on Earth. One way to alleviate this is to reduce the use of such fuels. An alternative method is to capture and store the emitted $CO_2$ to stop it from polluting the atmosphere. This is known as carbon capture and storage. This study discusses the methods and economics associated with the same.*

**Keywords:** Carbon capture and storage, climate change, global warming, greenhouse gases.

MOST industries and power stations today are dependent upon the exploitation of fossil fuels, i.e. coal, oil and natural gas to meet their demands. While these energy sources are able to meet the needs to a large extent, they have various problems associated with them. The aforesaid fuels are all hydrocarbons and primarily release carbon dioxide ($CO_2$) on combustion.

Apart from $CO_2$, these fuels are also known to emit other gases such as methane, oxides of sulphur, oxides of nitrogen and carbon monoxide, to name a few. These gases, which allow the incoming solar radiation to pass through but do not allow the trapped heat to escape, are known as greenhouse gases (GHGs). These gases, in the right proportions are necessary for human survival on planet Earth. However, their excessive release causes rise of temperatures on Earth. This process is known as global warming.

Over the last 100 years, global mean surface temperature has increased by $0.74 \pm 0.18$°C. Moreover, the rate of warming over the last 50 years ($0.13 \pm 0.02$°C per decade) is double that over the last 100 years ($0.07 \pm 0.02$°C per decade)[1]. Figure 1 shows this warming very effectively. This rise is alarming as it could lead to widespread melting of polar ice-caps which might result in submerging of low-lying areas.

This crisis can be solved by reducing the current energy thrust on fossil fuels and shifting to unconventional sources of energy. However, such sources have a high establishment cost, are location-dependent and their pricing has not been competitive enough. Hence, if we are to meet the 8–9% economic growth, drastic cuts in fossil fuel usage cannot be considered feasible. This is because no country in history has improved its level of human development index without corresponding increase in per capita use of energy[2]. This has been shown in Figure 2. Nevertheless, efforts to reduce $CO_2$ emissions have been undertaken. The maximum potential to reduce is present in five sectors, viz. power, energy-intensive industry, transport and habitats, forestry and agriculture[3]. It is a myth that these reductions are low cost. However, according to the MARKAL model, the undiscounted incremental energy system costs are US$ 800 billion and the undiscounted energy system costs are in excess of US$ 1 trillion for $CO_2$ reduction of 30% (ref. 2). Even then, these reductions may not prove to be enough given the harm that human civilization has already caused to the Earth.

Martin Rees writes in the Foreword of the report 'Geoengineering the climate'[4], that if the reductions achieve too little, too late, there will surely be pressure to consider a 'Plan B', which will involve counteracting the effects of GHG emissions through geoengineering. Geoengineering refers to modification of a planet's natural environment through various technologies to counteract anthropogenic climatic change. Geoengineering is based on two planks[4].

- Carbon dioxide removal (CDR) techniques which remove $CO_2$ from the atmosphere, which involve several methods including enhancing $CO_2$ sinks, the use of biomass for carbon sequestration, use of natural weathering processes to reduce $CO_2$ in air, etc.
- Solar radiation management (SRM) techniques that reflect a small percentage of the Sun's light and heat back into space.

Carbon capture and storage technology, which is one of several carbon sequestration methods, is an innovative

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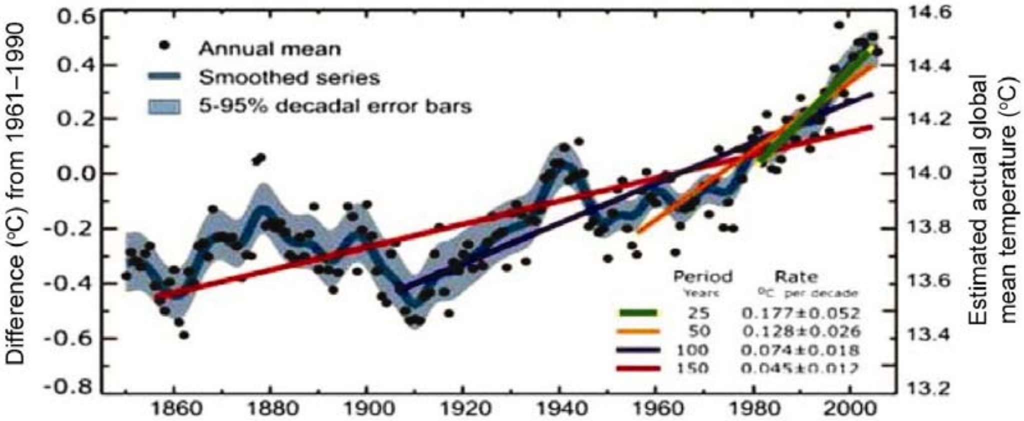


**Figure 1.** Rise in global mean temperatures from 1961 to 1990. Notice the steep curve of green than the red clearly indicating that the rate of warming is increasing per decade. (Source: ref. 1.)

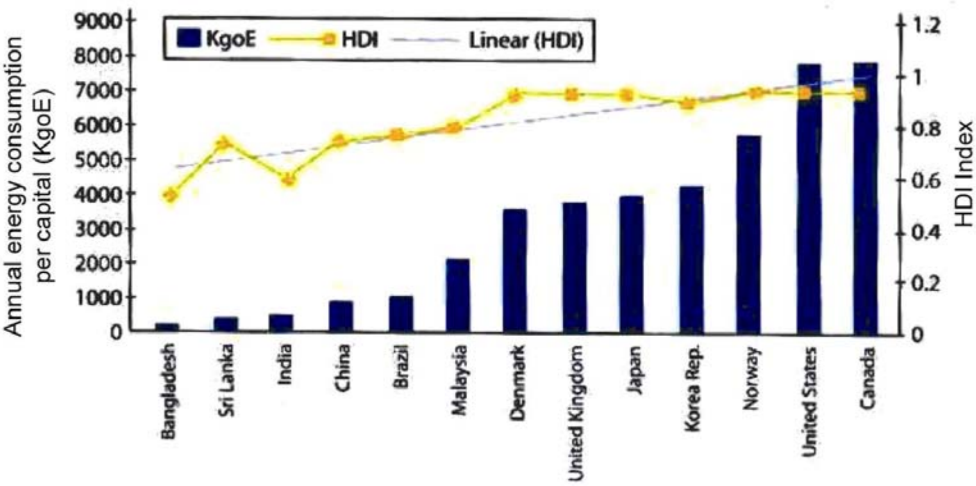


**Figure 2.** An international comparison between human development index and per-capita energy consumption (in KgoE). Source: World Development Indicators Database (adapted from ref. 2).

method to mitigate global warming and the primary focus of this study. As the name suggests, in this method, $CO_2$ emitted from thermal power plants and $CO_2$ intensive industries is captured and stored in various reservoirs to lessen their polluting impact on the atmosphere. CCS is therefore hailed as the technology of the future. As our dependence on fossil fuels is not expected to decline radically in the near future, CCS can provide an excellent transition from conventional to non-conventional methods of generating power, such as solar power, wind power, geothermal energy, etc. CCS is referred to as ‘fictitious reduction’, since there is no decrease in the emission of $CO_2$ from the Earth, but the polluting impact is lessened.

The entire process involves three processes: capture, transport and storage of the $CO_2$. These methods have been discussed in this article. In the later half of the article, the economic factors associated with CCS have also been discussed. Figure 3 shows the various steps.

## Capture of the $CO_2$

The first step of CCS is to separate $CO_2$ from other gaseous substances since the chimney smoke in power-plants contains only 10–12% $CO_2$. This process is known as carbon capture. Technologically, this is considered to be the most difficult part of the entire CCS mechanism. Also, carbon capture happens to be an expensive process as per the current developments. Capturing $CO_2$ can be achieved using three following methods.

### *Post-combustion separation*

The post-combustion separation method involves separation of $CO_2$ from the flue gas emitted from thermal power plants. This involves chemical adsorption of the gas in a solvent. For instance, certain amines such as monoethanolamine or ammonia (using the chilled ammonia process) can be used as solvent[5]. Fuel gas is passed through

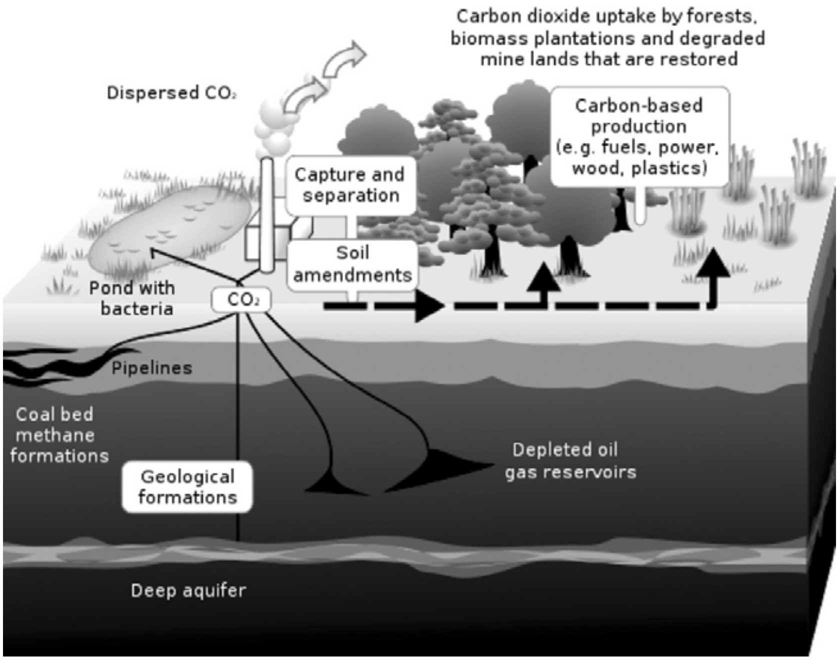


**Figure 3.** Carbon capture and storage schematic. Source: http://en.wikipedia.org/wiki/File:Carbon_sequestration-2009-10-07.svg

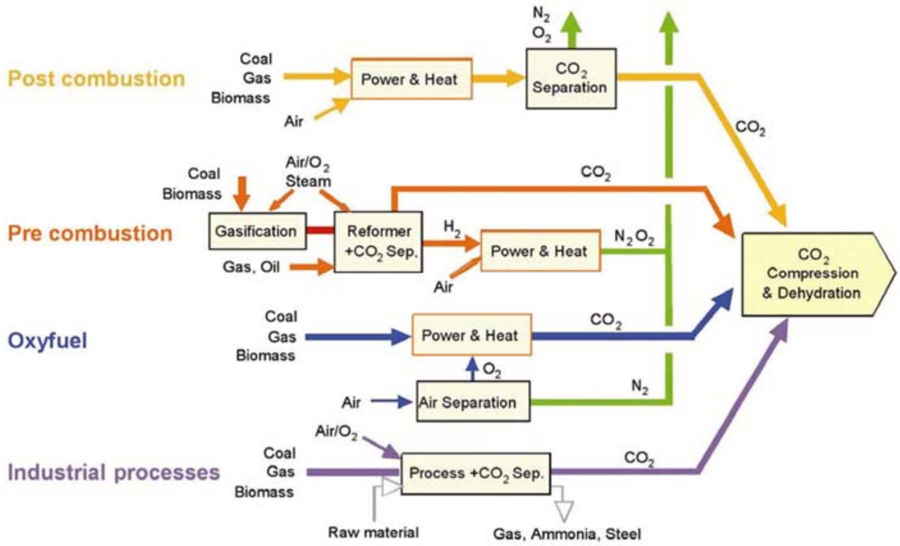


**Figure 4.** Overview of $CO_2$ capture processes and systems. Source: ref. 5.

the solvent at relatively low temperatures of about 40–50°C and then the $CO_2$ is obtained by regeneration of the solvent at temperatures of more than 100°C. The energy penalty for this method is regeneration of the solvent[6].

*Oxyfuel separation*

Oxyfuel separation is the scientifically most advanced way of $CO_2$ capture. Whenever a fuel such as coal, oil or natural gas is burnt in air, the emitted $CO_2$ combines with other components of air including nitrogen whose composition in air is about 78%. The oxyfuel separation method thus involves filling of the entire combustion chamber with almost-pure oxygen and hence the emission obtained is almost entirely $CO_2$. This is done using an air separation unit (ASU), which works on the cryogenic principle. The energy penalty in this method is in the working of the ASU[6].

*Pre-combustion separation*

Pre-combustion separation involves gasification of the fuel such as coal. The fuel is reacted with steam so as to convert it to carbon monoxide and hydrogen. This mixture is known as synthesis gas (syngas) mixture.

$$\underset{\text{Carbon}}{C} + \underset{\text{Steam}}{H_2O} \rightarrow \underset{\text{Carbon monoxide}}{CO} + \underset{\text{Hydrogen}}{H_2}$$

This mixture is then again reacted with steam to form carbon dioxide and hydrogen in a reaction known as the 'water-gas shift' reaction.

$$\underset{\text{Carbon monoxide}}{CO} + \underset{\text{Steam}}{H_2O} \rightarrow \underset{\text{Carbon dioxide}}{CO_2} + \underset{\text{Hydrogen}}{H_2}$$

Carbon dioxide so formed is captured and the hydrogen obtained in the above two steps is used as a clean fuel.

For further reading on $CO_2$ capture, the reader may refer to refs 7–12. Figure 4 illustrates through a flowchart, all the capture mechanisms involved.

## $CO_2$ transport

After $CO_2$ has been captured by any of the aforesaid methods, it needs to be transported to the storage site. This can be done in several ways – pipelines, boats, railways or trucks. It is suggested that the initial pilot projects may involve transportation through trucks or boats, but it may prove to be costly when done on large-scale. Therefore, pipeline transportation is considered to be most viable[6].

The pipelines used must be of good quality as any compromise with it may lead to $CO_2$ leak, which is discussed later. Of course, carbon dioxide is not combustible like natural gas, which is rather inflammable. So, $CO_2$ transportation is more of an economic rather than a technological barrier.

## $CO_2$ storage

After the captured $CO_2$ has been transported to a potential storage site, it needs to be stored. The $CO_2$ may be stored in geological formations or oceans. The choice of the storage site depends upon the $CO_2$ storage potential and cost-effectiveness. $CO_2$ storage in oceans was initially conceived as a possible option, but due to very high environmental risks, it is no longer considered one[13].

## Geological sites for sequestration of $CO_2$

Geological method of $CO_2$ sequestration is scientifically the most discussed and popular topic. Geologically, $CO_2$ may be stored in basalt formations, deep saline aquifers, unmineable coal seams and depleted hydrocarbon reservoirs.

### *Basalt formations*

Basalt is a volcanic rock composed of silicates of metals such as aluminum, iron and calcium which can combine with $CO_2$ to form carbonate minerals. They are very good for storage of $CO_2$ as they can isolate it from the atmosphere for a very long period. The advantages of storing $CO_2$ in basalt formations are enormous, some of them being[14]:

- Basalts provide solid cap rocks and thus high level of integrity for $CO_2$ storage.
- Basalts react with $CO_2$ and convert the $CO_2$ into mineral carbonates which provide high level of security.
- Tectonically, the traps are considered to be stable.

### *Deep saline aquifers*

Saline aquifers refer to water reservoirs which are not a source of potable water due to their saline nature. They are considered to be one of the best storage sites as they have a huge potential for storage of $CO_2$ and also due to their geographical ubiquity[15].

### *Unmineable coal seams*

Unmineable coal seams offer a very attractive and seemingly profitable method of storing $CO_2$. Coal contains adsorbed methane which is extracted by depressurizing coal seams as a result of pumping out water. This is known as coalbed methane and is an excellent fuel. However, at deeper depths such recovery is not economically feasible. Thus, the captured $CO_2$ can be injected in such seams, which improves methane recovery. This is known as enhanced coalbed methane recovery ($CO_2$–ECBM). It is seen that the injection of $CO_2$ not only improves methane extraction, but also helps to make the adsorption of $CO_2$ much more rapid[16].

### *Depleted oil and gas reserves*

The depleted oil and natural gas reserves are another potential storage location for $CO_2$. Here, $CO_2$ is injected into such depleted hydrocarbon reservoirs which improves recovery of the hydrocarbons. This method known as enhanced oil recovery ($CO_2$–EOR), if developed well, will be of great use in areas such as Europe and India which do not have an extensive reserve of oil and natural gas. A study estimates that in a high price scenario, the annual incremental oil production could reach 180 million barrels and around 60 million tonnes of $CO_2$ could be stored annually with the help of $CO_2$–EOR[17].

It is noteworthy that while basalt and saline aquifers do not provide any added benefit except storage, unmineable coal seams and depleted hydrocarbon reserves offer more efficient extraction of energy resources and thus are likely to be tried out earlier.

## Geological storage potential of $CO_2$: India and the world

The exact global storage potential is difficult to determine, given the wide variety of geological formations around the world, a number of which remain unidentified. However, it can emphatically be stated that there is a huge potential for $CO_2$ storage worldwide. An estimate of the global sequestration potential in geological formations suggests that $CO_2$ storage potential is of the following order[18].

- Deep saline formations: $10^2$ to $10^3$ Gt of $CO_2$.
- Depleted oil and gas reserves: $10^2$ Gt of $CO_2$.
- Coal seams: $10^1$ Gt of $CO_2$.

According to IPCC, there are about 2000 Gt of likely $CO_2$ storage in geological formations[5]. This includes 675–900 Gt of $CO_2$ in oil and gas fields, 1000– ~ 10,000 Gt of $CO_2$ in saline formations and 3–200 Gt in coal beds.

This is a considerably large figure given that the annual $CO_2$ emissions add up to 33.5 Gt in 2010 (GlobalCarbonProject.org)[18]. Further, it is expected to decrease if further changes take place in terms of proportions of fossil fuel usage. Figure 5 demonstrates the $CO_2$ emissions in various scenarios. The figure illustrates that alternative policies and better efficiencies for existing fossil fuels could provide 16% mitigation from $CO_2$ emissions as compared to business-as-usual till 2030.

The two most commonly cited studies with respect to geological storage potential of $CO_2$ in India are Singh *et al.*[19] and Holloway *et al.*[20]. A few other studies have been conducted as well. The following two major studies give widely varying results.

- Singh *et al.*[19] state that there is a storage potential of 572 Gt of $CO_2$.
- In contrast, Holloway *et al.*[20] suggests a much lower potential of only 68 Gt of $CO_2$.

The major cause for this discrepancy is that while both studies suggest almost equal storage potential for coalfields and oil and gas reserves, the former indicates a storage potential of 360 Gt of $CO_2$ in saline aquifers, which the latter estimates to be only about 59 Gt. The latter study gives no estimation for storage in basalt formations. Other widely varying data also exist.

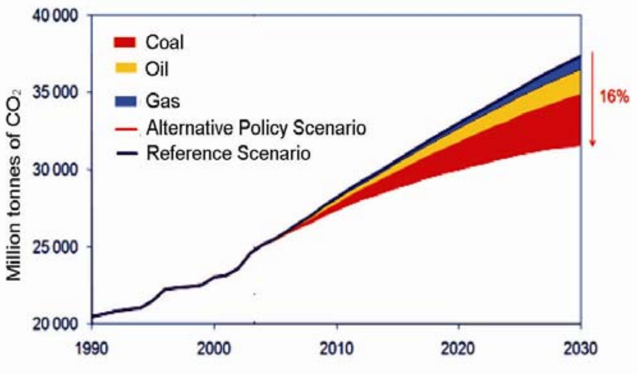


**Figure 5.** Annual $CO_2$ emissions in various scenarios. (Source: IEA World Energy Outlook[39]).

The CCS global study[21] carried out by the Wuppertal Institute for Climate, Environment and Energy has compiled the two above studies and another study by Dooley *et al.*[22] (Table 1).

It is noteworthy that all such estimates are just indicators. Widely contradictory views also exist. Narain[23] suggests that $CO_2$ storage sites are not restricted by geography or geology, while Doig[24] states that there are by no means enough $CO_2$ storage sites in Indian geological formations. Thus, a much greater degree of research needs to be carried out in this area.

## Industrial usage of $CO_2$

Carbon dioxide is an important chemical for several industries and has numerous industrial applications. In fact, enhanced oil recovery (EOR) and enhanced coalbed methane recovery (ECBM) are considered as industrial applications by many. Apart from these, the other important areas of $CO_2$ usage are urea fertilizer production, food packaging and processing, beverage carbonation, pharmaceuticals, fire suppression, winemaking, paper and pulp processing, water treatment, steel manufacturing, etc. Prospective areas of $CO_2$ usage include polymer processing, concrete curing, algal bio-fixation, renewable methanol generation, etc.

Industrial usage of $CO_2$ can help the cause of CCS through the following[25].

- Additional revenues which can result in more demonstration projects and accelerate the reduction of technology costs, specifically those related to capture.
- CCS project delivery experience of addressing financial, environmental and regulatory barriers.
- Public acceptance of technologies and projects.

Table 2 indicates the $CO_2$ usage areas and are shortlisted by potential future demand.

## Economics of CCS

Carbon capture and storage technology is governed by two major factors or the two ‘eco’s – ecology and economy. While it is one of the important ways to potentially reduce $CO_2$ emissions, it has its own share of economic penalties, similar to other clean technologies.

The IPCC suggests an additional electricity cost of US$ 0.01 to 0.05 per kilowatt-hour of electricity generated through CCS-based power plants as compared to

**Table 1.** Overview of existing estimates for theoretical storage capacity in India

| | Dooley *et al.*[22] | Singh *et al.*[19] | Holloway *et al.*[20] Good, fair and limited quality | Holloway *et al.*[20] Good and fair quality | Holloway *et al.*[20] Good quality |
|---|---|---|---|---|---|
| Oil fields | – | 7 | | 10.0–1.1 | |
| Gas fields | 2 | | | 2.7–3.5 | |
| Aquifers | 102 | 360 | 138 | 59 | 43 |
| Coal seams | 2 | 5 | | 0.345 | |
| Basalts | – | 200 | | – | |
| Total | 104 | 572 | 142 | 63 | 47 |

Source: Refs 21 and 40.

**Table 2.** Shortlisted industrial uses of $CO_2$ by potential future demand (> 5 Mtpa)

| Existing uses | Current non-captive $CO_2$ demand (Mtpa) | Future potential non-captive $CO_2$ demand (Mtpa) |
|---|---|---|
| Enhanced oil recovery (EOR) | 30 < Demand < 300 | 30 < Demand < 300 |
| Fertilizer – urea (captive use) | 5 < Demand < 30 | 5 < Demand < 30 |
| New uses | | Future potential non-captive $CO_2$ demand (Mtpa) |
| Enhanced coalbed methane recovery (ECBM) | | Demand > 300 |
| Enhanced geothermal systems – $CO_2$ as a working fluid | | 5 < Demand < 30 |
| Polymer processing | | 5 < Demand < 30 |
| Algal bio-fixation | | > 300 |
| Mineralization | | |
| Calcium carbonate and magnesium carbonate and sodium bicarbonate | | > 300 |
| $CO_2$ concrete curing | | 30 < Demand < 300 |
| Bauxite residue treatment (‘red mud’) | | 5 < Demand < 30 |
| Liquid fuels | | |
| Renewable methanol | | > 300 |
| Formic acid | | > 300 |

Source: Ref. 25.

existing power plants and US$ 20–270 per tonne of $CO_2$ avoided[5]. This cost can be supplemented by suitable carbon trading mechanisms, and also by EOR and ECBM technologies as discussed earlier. The Sleipner project in Norway was possibly successful because of the Norwegian offshore carbon tax[26]. Statoil, the company operating this project preferred to invest US$ 55/tC instead of the heavy carbon tax of US$ 140 in Norway.

The CCS component cost for each tonne of $CO_2$ avoided is US$ 15–75 for capture, US$ 1–8 for transport and US$ 0.5–8 for injection into geological sites. Revenues from storage are estimated at US$ 360 per million tonnes or US$ 0.00036 per tonne of $CO_2$ annually. Over a hundred year period, the revenue is only US$ 0.036 per tonne of $CO_2$. This is too small compared to the cost of CCS. Thus, the revenue generated is almost negligible when compared to cost.

Another study indicates that sequestering 90% of the $CO_2$ from power plants would add 2¢/kWh$_e$ to the busbar costs[27]. At this price, CCS compares favourably with renewable and nuclear energy sources[26]. This competitive price position could however change in the future, owing to a variety of factors such as rise in fossil fuel prices, change in technological scenarios, etc. Thus, there needs to be a focus to make CCS cheaper and more affordable, especially for the developing countries. This can be done by innovations within the technology. The cost could of course be brought down if ECBM or EOR recovery takes place as discussed earlier. The pre-combustion route opens up opportunities for ‘polygeneration’, in which apart from electricity, other side products are also generated[26]. For example, the hydrogen produced could be used as a fuel. Moreover, syngas is an important mixture for several chemical reactions. Other advances could include the development of a membrane contractor[28], which reduces the size of the absorber and stripper units by 65% and solvent loss. Such advances would help the cause of CCS as a technology. This is the reason why $CO_2$ storage in oceans is no longer considered to be an option

When we consider CCS as a mitigation option towards climate change, it is certainly a delight for the technologist and the environmentalist, but the economist is not always pleased. Therefore, the question arises that if we compare CCS with renewable energy sources, such as solar energy, wind energy, geothermal energy, etc. what is likely to be the correct mitigation option, both in the near term and the long term.

If we look at the environmental impacts, the GHG emissions of renewable energy plants are a very small fraction of CCS-based fossil fuel power plants. By 2020, offshore winds would emit only 5–8%, solar thermal energy 11–18% and photovoltaics 14–24% of the emissions as compared to CCS power plants[21]. Thus, the environmental sustainability in case of renewable energy sources is far better than CCS.

Speaking of economics, the above cited report also predicts that fossil-fuel-fired CCS plants would produce electricity at a more expensive rate than renewable energy for all fossil fuels except lignite after 2020 and after 2025 for lignite[21]. Thus, economically also, renewable energy sources might dominate in terms of the potential to cause GHG reduction at an affordable cost. It may, however, be noted that this timeline might not be exact. The global economic slowdown must definitely have had an impact on the global willingness to pay for reduction of $CO_2$ emissions and thus the use of CCS and subsequently renewable energy sources might be postponed by some years and possibly a couple of decades.

So, what exactly is the role of CCS? This has been very well stated by the Editor of *Greenhouse Gas Science and Technology*, 'CCS is an important transition technology such that we minimize the $CO_2$ emissions and at the same time develop renewable resources'[29].

A major factor determining the success of CCS will be the monetization of $CO_2$ emissions. There are two possible ways of doing this. The first is as discussed with regards to the Sleipner project, i.e. imposition of taxes on heavy emitters. Another way is the emission trading mechanism. This method involves an upper limit on how much $CO_2$ a country can emit. If the country emits less than this fixed amount, it can use it as a market commodity to trade with and earn monetary profits. This mechanism is an integral part of the Kyoto Protocol[30]. The carbon price at which CCS is likely to be effective is US$ 200, which is the maximum price indicated by EPPA modelling efforts for the year 2040. If this is done, it will provide a real boost to CCS[31].

For example, a US$ 200/tC charge on emissions would yield a 50% reduction in emissions without CCS but an 80% reduction in emissions with CCS. These results demonstrate the potential role of CCS in the electricity supply sector[32].

## Problems, risks and challenges

However there are a few problems, risks and challenges associated with carbon capture and storage.

1. When carbon dioxide is stored, it must be done in a way to ensure that it does not leak. Any sort of leak would not only damage the environment but also wastage of money invested in the process. Carbon dioxide leak may also lead to death of people due to asphyxia. Leakage may occur in several forms. One most common way is leakage during injection of $CO_2$. It may also leak during transport. Therefore, during the entire CCS process, proper quality of the materials of the wells, pipelines, etc. must be maintained.

2. Oceans are a prominent $CO_2$ sink. However, there has been a concern cited that the trapped $CO_2$ may make the water acidic if precautions are not taken, thus rendering it useless for the use of future generations. It may also disrupt marine life thus affecting biodiversity.

$$\underset{\text{Carbon dioxide}}{CO_2} + \underset{\text{Water}}{H_2O} \rightarrow \underset{\text{Carbonic acid}}{H_2CO_3}$$

3. Many believe a major challenge with carbon capture and storage is expected to be changing the perception of the people to accept it as a good technology. This would involve education of the people about it. Many countries such as the Netherlands and the USA have already initiated projects to make the people more aware of the CCS technology. The research community needs to reach out to the general public on the use of the technology. It must be understood that the general public must be willing to spend more for climate change abatement options and thus CCS must be made acceptable to them.

4. Traditionally, $CO_2$ sequestration is considered to be an expensive technology. As a result, many governments, especially those of the developing countries do not have a favourable stance towards CCS. This has been detrimental to research and development on CCS. Such research must be supported. Policy makers must be aware of the advantages of this technology. At the same time, it is also true that CCS involves an additional energy penalty of 33% as compared to ordinary fossil-fuel-fired power plants and thus researchers must focus on making this a more economic process[29].

5. A recent article reports that CCS technology can possibly create seismic hazards and have a tendency to create earthquakes[33]. However, it is also noteworthy that this was contradicted by the response of Juanes *et al.*[34], which again has been rebutted by the authors of the original paper[35]. For a summary of the arguments present in the article, the reader may refer to the comments of Stuart Hazeldine[36].

## History and current status of CCS

Initially before the 1990s, CCS comprised very small and disintegrated research groups. Funding was difficult to procure for research in this area. The first major breakthrough came in March 1992, through the organization of the First International Conference on Carbon Dioxide Removal in which around 250 scientists from 23 countries participated. This conference later grew into the International Conference on Greenhouse Gas Control Technologies (GHGT). This was followed by the formation of several important bodies for coordinating CCS activities such as United Kingdom Carbon Capture and Storage Consortium (UKCCSRC), the International Energy Association Greenhouse Gas Programme (IEAGHG), the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), etc. Today, CCS is considered to be at the forefront of environmental research. Several journals, such as the *International Journal of Greenhouse Gas Control* (Elsevier) and *Greenhouse Gases: Science and Technology* (Wiley), dedicated to CCS research have come up.

The Global CCS Institute based in Australia suggests that there are 74 large-scale integrated pilot projects on CCS around the world. Out of these, only eight are under operation and the rest are in the stage of execution, definition or planning. Moreover, only 8 of the 74 projects belong to developing countries, 5 to China, 2 to Middle East and 1 to Algeria. Most of the projects under operation or those sanctioned are based in Australia, USA and European countries[37].

The IPCC[5] divides the various component technologies of CCS into the following phases.

- Research Phase: Ocean storage (We must understand that this report was prepared in 2005 and at that time ocean storage was considered a probable option).
- Demonstration Phase: Oxyfuel combustion, enhanced coalbed methane recovery.
- Economically feasible under specific conditions: post-combustion, pre-combustion, storage in gas and oil fields, storage in saline aquifers.
- Mature market: industrial separation, enhanced oil recovery.
- Transport lies in the interface phase between Phases 3 and 4.

Earlier, it was expected that the first Commercial CCS Project would be initiated around 2050. However, the global economic downturn has had a retarding impact on the development of the technology.

In India, the technology is yet to spread its boundaries outside the laboratory-scale. The sequestration potential for various storage methods has been assessed but have not been applied on a project-based scale. India lacks a programme similar to the United States Department of Energy Partnership Program, the $CO_2$CRC Programme or the IEAGHG Programme, which have been beneficial for the development of CCS in the USA, Australia and Europe respectively.

## Conclusions and recommendations

As stated earlier, our dependence on hydrocarbons is not expected to decline in a major way given the current economic scenario. So, CCS is an important transition technology such that we minimize the $CO_2$ emissions and at the same time develop renewable resources[25]. We must also understand that CCS does not compete with renewable energy sources, it rather complements them. The development of CCS is necessary because availability of a larger number of abatement options would mean greater ease in combating climate change[26].

It is generally predicted that carbon capture shall first start from coal-fired power plants, primarily because the $CO_2$ emitted per tonne of coal burnt is quite larger than that emitted from 1 tonne of oil or natural gas burnt and hence capture shall be more economical[6]. This is also more probable due to the fact that many major economies of the world such as the USA, China and India meet their primary energy demand from coal.

CCS needs to be supported well. Thus, carbon credits shall play an important role in its implementation on a large scale. Moreover, since CCS is largely regarded as the technology of the future, the knowledge of CCS should not be restricted to scientists and professors, but also be shared with school and college students through various invited talks, articles, exhibitions, etc.

For fast and efficient development, CCS needs a highly multi-disciplinary working group involving petroleum engineers, chemical engineers, geologists, geophysicists, mathematicians and other scientists. The technology needs a favourable collaboration between industry, research laboratories, universities and policy makers. It is suggested that in India, a national network project should be set up with the joint funding of the government, industry and foreign collaboration should also be tried out. The project may comprise CSIR Laboratories, companies such as CIL and ONGC and also academic institutions such as IITs, ISM and various other state and national universities.

Currently, the technology is advancing well, but in fragments. R&D on capture, transport and storage is being carried out. Once this is done, there shall be need to integrate the various processes. If developed the right way, CCS has the potential to reduce the current emissions in fossil-fuel-fired power plants by up to 90%[25].

While it is true that the Stern Review and the International Energy Agency's World Energy Outlook Report have listed CCS to be one of the carbon mitigation strategies for India, the development of CCS in India has been somewhat slow. Kapila and Haszeldine[38] suggest that this is because of India's coalition form of government in the recent times and the fragment bureaucratic structure, which result in 'too many cooks' and makes any sort of innovation difficult. They are of the view that CCS should follow the footsteps of the IT sector, wherein growth has been facilitated by private sector led R&D. However, in most developing countries including India, there has been some degree of apprehension about CCS as the technology is expensive and involves a number of risks. The general desire among developing countries is that the Western countries try it first on their soil and then transfer it to the developing ones[3]. However, this may also mean that the developing countries are left behind in research on CCS, which might become a crucial technology in the days to come. The only possible way to understand CCS in its entirety is to perform more interdisciplinary research involving technology development, technology forecasting, economic and environmental assessment and vulnerability assessment.


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