J. Integr. Sci. Technol. 2024, 12(2), 728 Review

Journal of Integrated
SCIENCE & TECHNOLOGY

Carbon Capture and Storage: Current state, emerging materials, and future directions for mitigating climate change

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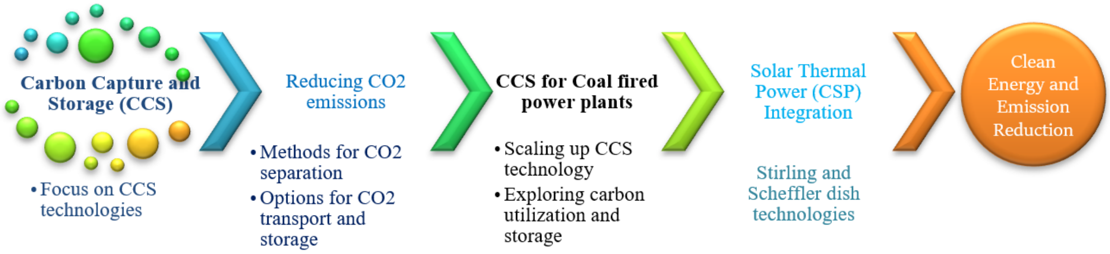
Received on: 15-Jul-2023, Accepted and Published on: 27-Sep-2023

ABSTRACT



This study provides an analysis of carbon capture and storage (CCS) technologies as a crucial method to reduce carbon dioxide (CO_2) pollution along with addressing climate change. The discussion includes the current state of carbon sequestration techniques, including pre- and post-combustion methods, and explores the potential of various materials for carbon capture. The study also examines challenges related to scaling up CCS, regulatory frameworks, and carbon utilization and storage. The findings highlight significant advancements in CCS technologies but emphasize the need for further research and development to fully realize their potential in mitigating climate change. The study also discusses the importance of reducing CO_2 emissions and explores Scheffler dish and Stirling dish technologies for removing atmospheric CO_2 using concentrated solar power. Overall, this research emphasizes the significance of CCS technologies and the importance of accessible solutions for reducing CO_2 emissions.

Keywords: Carbon Emission, Carbon Capture, Materials, Process Integration, CO_2 Emissions reduction, Concentrated, Solar power, Scheffer dish, Stirling dish.

INTRODUCTION

One of the main issues raised by global leaders and specialists on the topic, in addition to everyday discourse or the media, is the worry about climate change. The primary source of this worry is thought to be carbon dioxide (CO_2) emissions. Consequently, it makes sense that lowering these emissions might help to mitigate the issue of climate change.[1] The American Oceanic and Ministry Of environment (NOAA), which runs the Puna Loa Laboratory and is in charge of keeping track of atmospheric CO_2 levels, provided the information on CO_2 concentration globally, which is represented in Figure 1. Energy production and storage (CCS) are essential components in the fight against climate change, which is unquestionably a greatest threat to our planet. Despite the fact that CO_2 emissions have long been a cause for concern in the world, there hasn't been much, if any, consistent progress. The principal driver of anthropogenic CO_2 emissions, which as of 2018 contributed to 68 percent (or 37.5 $GtCO_2$) of the overall global Greenhouse gas emission levels of 55.3 $GtCO_2e$, is our dependence on fossil fuels. We now lack the resources and technology to run expense at the inter scale, which would be necessary to capture CO_2 in such huge volumes.[2]

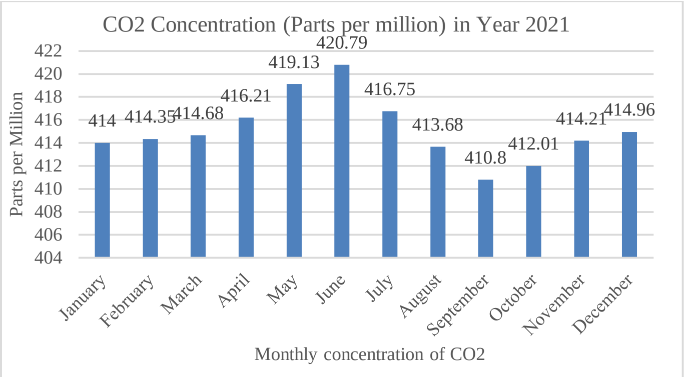


Figure 1. CO_2 Concentration (ppm) in year 2021. https://www.esrl.noaa.gov/

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Cite as: *J. Integr. Sci. Technol., 2024, 12(2), 728.*
URN:NBN: sciencein.jist.2024.v12.728

ISSN: 2321-4635
http://pubs.thesciencein.org/jist

In the past, photosynthesis—the process by which plants naturally take in CO_2 and sunshine and produce oxygen—was the main way that CO_2 was removed from the atmosphere. Plants alone, however, are no more able to absorb the amount of CO_2 naturally and handle the amount of carbon dioxide in the air due to recent fast industrial expansion.[3] Contamination and environmental deterioration have been brought on by accelerated economic development in various countries, and this issue is getting worse worldwide. Hence, a solution must be developed to guarantee the survival of both the present and future generations. The generation of too much greenhouse gases and other contaminants is one of the major problems the environment is currently facing. Several studies have demonstrated that the industrial sector's use of fossil fuels is responsible for CO_2 emissions of about 56%. Generally speaking, India's present emissions and projected future emissions are substantial enough having an impact on global mitigation efforts. Thermal power plants account for further than 65 percent of energy producing capacity of India, with coal accounting for over 85% of this capacity.[4] Only technology that may significantly cut emissions from these industrial operations and power plants is energy production and sequestration (CCS). Alternative energies are not mitigating replacements to CCS in the manufacturing industry. The most effective way to achieve global decarbonization is to include CCS in a portfolio of reduced technologies because it not only provides energy reliability but also lower costs.

The majority of individuals think that carbon capture and storage (CCS) technology has essential characteristics for reducing the atmospheric carbon dioxide (CO_2) emissions from power plants and other sizeable industrial facilities, that are the primary contributors of greenhouse gas emissions associated with global climate change. Moreover, there are significant obstacles to their usage, including the high energy requirements and elevating cost of present CO_2 capture techniques.[5] Today, a variety of methods are commercially available and frequently used to separate (capture) CO_2 from a mixture of gases, usually as a purification stage in an industrial process as shown in Figure 2. Since the majority of anthropogenic CO_2 is produced during the burning of fossil fuels, pre- or post-combustion systems are typically used to describe carbon di oxide capture methods in the CCS context, depending on whether carbon (in the form of carbon di oxide) has been collected pre- or post-combustion of fuel. A CO_2 collecting device is not necessary for oxyfuel, often known as oxy-combustion. Although some industrial processes (like those in the glass as well as metals sectors) do use oxygen combustion, this idea is not yet commercial but still in the developmental phase in the operation of power plant. However, these processes do not vanish CO_2 from the gas stream. The similar kinds of CO_2 collection devices which would be utilised in power plants are used in industrial operations that don't entail combustion.[6]

CARBON CAPTURE MATERIALS

Global warming as well as unfavorable climate change are both caused due to greenhouse gas accumulation, particularly CO_2 in the atmosphere. Coal-based power plants account for the majority of global energy production. Researchers, environmentalists, and industry stakeholders have given pre- and post-combustion technologies that capture carbon through a variety of technical alternatives, including membrane separations, absorption, adsorption, as well as chemical looping combustion with/without oxygen uncoupling, a lot of attention.

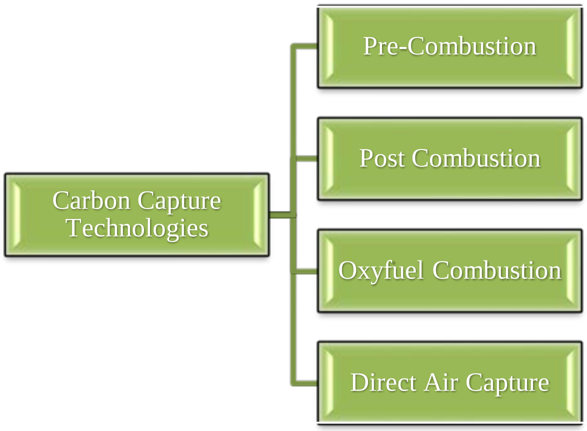

Figure 2. Carbon Capture Techniques

Here are a few current tactics for reducing CO_2 emissions and reducing positive emissions (Figure 3): (1) carbon capture, utilization, and storage (CCUS). (2) technologies that reduce emissions, including reforestation, afforestation, and bioenergy with carbon capture and storage (BECCS), DAC, as well as other methods. (3) rerouting energy output to renewable sources including wind, solar, nuclear, and hydro. Numerous material classes are either being investigated for carbon capture or are already in use. These consist of carbon nanotubes, cellulose, silica gel, zeolites, carbon nanotubes, activated carbon, MOFs, and others.[7]

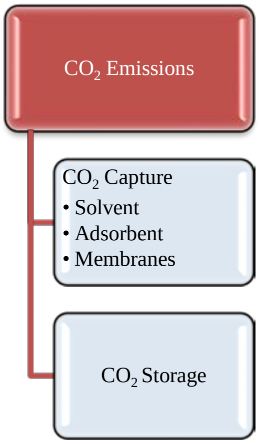

Figure 3. Schematic representation of Carbon Capture Techniques [7]

Solvents

Researchers use a variety of solvent materials for capturing carbon dioxide (CO_2) from industrial emissions, including: Aqueous Amine Solutions, like monoethanolamine (MEA) as well as ethanolamine (DEA), are the most commonly used solvents for CO_2 capture. These solvents can absorb large amounts of CO_2 and are relatively cheap, Ionic liquids Polyethylene Glycol (PEG), Polymeric Amine Solutions such as polyethylenimine (PEI), Switchable Solvents are materials that can switch between being hydrophilic and hydrophobic, depending on the conditions. Deep Eutectic Solvents (DES), Metal-Organic Frameworks (MOFs) have been comprised of metal ions or clusters connected with organic ligands. The choice of solvent is one of the substantial processes in carbon capture based on adsorption (Table 1). To lessen the production of waste byproducts, it is crucial to adhere to the fifth green chemistry principle and encourage the usage of cleaner solvents as well as auxiliaries.[8]

A solvent's volatility, vapor pressure, CO_2 solubility, propensity to foam, and corrosiveness all affect how effective it is. Furthermore, it's crucial to pick a solvent that won't harm the environment or release harmful byproducts. Using corrosive, viscous, or kinetically constrained solvents for broad scale gas separations in a realistic way is possible, according to Thomas Moore,[9] by microencapsulating the liquid solvents. The challenge of producing capsules on an industrial scale is a significant downside of the technique. Thus, a brand-new gel substance with a large surface area was suggested for carbon capture. SIPs, which are produced using a more scalable process, is a material that is comparable to MECS. Aqueous solutions of $K2CO_3$ as well as the ionic liquid DMEDAH Formate were included in high surface area SIP particles as well as sheets. The main goal of ION's test campaign was to show that its top solvent could operate steadily while sustaining at least 90% CO_2 removal for a minimum of 1,000 hours of operation .[10] In terms of kinetics, fast solvents react more CO_2 faster. This normally means that, contrary to what would be observed with a slower solvent, the temperature bulge in an absorption column rises more quickly and may reach a higher maximum bulging temperature. During design procedures, the management of a kinetically quick solvent might be taken care of. Faster solvents are frequently preferred to slower ones.

Table 1 Different Types of Solvents Used to Capture Carbon

Solvent	**Monoethanol amine (MEA)**	**Amino acid salts**	**Ammonia**	**Ionic liquids**
Ref.	**[18]**	**[19]**	**[20]**	**[21]**
Advantages	Widely used, good CO_2 capture capacity, well-established technology	Lower volatility, higher stability, efficient CO_2 capture	Low vapor pressure, high CO_2 capacity, less corrosive than MEA	Can be tailored for specific CO_2 capture requirements, low volatility
Disadvantages	High volatility, corrosive, can degrade over time	Limited research, potential high cost	High energy requirement for solvent regeneration	Limited research, potential high cost
Applications	Post-combustion CO_2 capture, natural gas processing	Post-combustion CO_2 capture	Post-combustion CO_2 capture	Post-combustion CO_2 capture, carbon capture from flue gas

Adsorbents

Carbon capture from flue gases might be obtained with micro and meso porous adsorbents. Researchers have also investigated various adsorbent materials for capturing carbon dioxide including (Table 2): Activated Carbon, Carbon Nanotubes, Silica Gel, Zeolites, Polymeric Resins such as polyacrylonitrile (PAN) and polyvinyl amine (PVAm). The selection of adsorbent material depends on factors like cost, efficiency, and environmental impact. It is also important to consider the regeneration process, as some materials may require significant energy input for regeneration.

The authors Sreenivasulu et.al.[11] discusses about carbonaceous (organic as well as metal organic 32 frameworks) along with non-carbonaceous (inorganic) porous adsorbents to absorb CO_2 under various process 33 conditions and pore sizes. The emphasis is also on non-carbonaceous micromaterials, such as a carbon molecular sieve (CMS-330) and a zeolite (13X-APG), in chemical looping combustion with in-situ CO_2 capture at high temperatures (>400o 34 C). This research was done in [12] while using carbon capture data based on experimental vacuum pressure swing adsorption (VPSA). The findings show that the carbon capture efficiency of the VPSA would increase to 96% for the 13X-APG and 84% for the CMS-330 if renewable energy were employed. Metal-organic frameworks (MOF) were used to create new montmorillonite, biochar, or aerosil composite materials in situ in [13]. Overall, three distinct MOFs—UTSA-16, UiO-66-BTEC, and CuBTC—had been employed. The produced adsorbents were investigated using energy-dispersive X-ray spectroscopy, scanning electron microscopy, powder X-ray diffraction, thermo gravimetric analysis, nitrogen adsorption porosimetry, and Fourier transform infrared spectroscopy. The results of the investigation showed that when aerosil was added to CuBTC (CuBTC-A-15), the quantity of CO_2 adsorbed rose by 90.2%, while when biochar was added to CuBTC (CuBTC-BC-5), the amount of CO_2 absorbed increased by 75.5% as compared to the pristine CuBTC attained in the study.

Table 2. Different Types of Adsorbents Used to Capture Carbon

Adsorbent	**Temperature**	**Pressure**	**Amount of Carbon Absorbed**	**Ref.**
Zeolites	Moderate to high temperatures (up to 250°C)	Low to moderate pressures (up to 20 bar)	Up to 8 wt%	[12]
Activated Carbon	Room temperature to moderate temperatures (up to 100°C)	Low to moderate pressures (up to 10 bar)	Up to 5 wt%	-
Metal-organic frameworks (MOFs)	Moderate to high temperatures (up to 200°C)	Low to high pressures (up to 50 bar)	Up to 20 wt%	[13]
Amine-modified silica	Moderate temperatures (up to 80°C)	Low to moderate pressures (up to 5 bar)	Up to 5 wt%	[22]
Polymer-based adsorbents	Moderate temperatures (up to 100°C)	Low to moderate pressures (up to 10 bar)	Up to 5 wt%	[23]

Membranes

Being one among the assuring approaches for carbon capture and separation, Membrane technology is gaining great attention. Membrane-based CO_2 capture involves the use of a thin membrane that selectively permeates CO_2 molecules while allowing other gases, like oxygen and nitrogen, to pass through (Table 3). The following is a general process description of CO_2 capture using membranes:

- Gas Separation: The flue gas has proven to be the first compressed to increase the pressure and then fed into the membrane module, where it comes into contact with the membrane. Due to the selective permeation of CO_2 through the membrane, a stream of concentrated CO_2 is produced on the permeate side of membrane, while a stream of gas depleted in CO_2 has been produced on feed side of the membrane.
- CO_2 Purification: The CO_2-enriched permeate is then further purified to remove any remaining impurities, such as water and sulfur compounds, before it is compressed and stored or transported for utilization or storage.

Four unique types of newly developed organic-containing micro-porous compounds that exhibit effectiveness for CO_2 separation for membrane usage have been discussed in-depth by Nicholas Prasetya et.al.[14] These compounds comprised of porous organic (PO) frameworks, metal-organic (MO) frameworks, thermally rearranged (TR) polymers, and polymers with intrinsic microporosity (PIMs). Each of these processes may produce both completely natural and composite microporous membranes, giving producers of membranes a variety of options. Further, R. Sharifian et.al.[16] suggested an eco-friendly technique for collecting oceanic-dissolved inorganic carbon (DIC) using bipolar membrane electrodialysis (BPMED) and electrochemical pH-swing technique. He investigates in situ mineral formation with natural and artificial seawater as well as an alkaline transformation strategy. The energy needed for oceanic-DIC capture could be greatly decreased by introducing an in-situ pH-swing within the BPMED cell. Theoretically, the thermodynamic energy required to collect Calcium carbonate through in situ mineralization is around 35 kilo Joules mol1 calcium carbonate which is only ten percent of the success.[16] This is true for a minor pH fluctuation (for example, basic pH 10.0 and acid pH 4.5, culminating in a pH of 5.5). It is important to note that the irreversible BPM-overpotential consumes over fifty-five percent of the required electrical energy. Therefore, the most effective method for reducing energy losses is to concentrate on membrane engineering, notably in attaining quick Wide Dynamic Range processes in the BPM, adding extremely permeable ion-exchange sections to remove carbon monoxide-ions, and optimizing layer thickness.

Focusing on Jian Guan et.al.[17] work, there has been a lot of study done on mixed matrix (MM) membranes made with metal-organic (MO) frameworks for capturing carbon in the attempt to fight regarding global warming. By creating machine learning methods specifically designed for (MM) membranes based on (MO) frameworks, Guan improves the subject. High-performance (MM) membranes for collecting carbon have been made possible by combining quantitative and ML approaches. The author's models use RF and transfer learning techniques to forecast separation performances for Carbon-dioxide/Methane and Carbon-dioxide/Nitrogen in addition to guiding the design of (MO) frameworks for (MM) membranes.

Table 3. Different Types of Membranes Used to Capture Carbon

Membrane	**Temperature**	**Pressure**	**Amount of Carbon Absorbed**	**Advantages**	**Disadvantages**	**Ref.**
Polymeric membranes	Moderate temperatures (up to 100°C)	Low to moderate pressures (up to 20 bar)	Up to 0.5 mol/L	Low cost, scalable, commercially available	Low selectivity, susceptible to degradation, limited lifespan	[24]
Ceramic membranes	High temperatures (upto 600°C)	High pressures (up to 30 bar)	Up to 1 mol/L	High selectivity, high durability, long lifespan	High cost, limited scalability, high manufacturing complexity	[25]
Composite membranes	Moderate to high temperatures (upto 200°C)	Moderate to high pressures (up to 50 bar)	Up to 1 mol/L	Tunable selectivity and permeability, potentially low cost	Limited commercial availability, potential manufacturing complexity	[26]
Liquid membranes	Moderate to high temperatures (upto 100°C)	Low to moderate pressures (upto 5 bar)	Up to 1 mol/L	High selectivity, potentially low cost, can be easily regenerated	Limited durability, potential leakage, safety concerns	[27]
Mixed matrix membranes	Moderate to high temperatures (upto 200°C)	Low to moderate pressures (upto 20 bar)	Up to 0.5 mol/L	Tunable selectivity and permeability, potentially low cost	Limited commercial availability, potential manufacturing complexity	[28]

Carbon Capture Process Integration

The process integration of carbon capture involves designing and optimizing the capture system to be integrated into existing industrial processes or power plants. This involves selecting the appropriate capture technology, optimizing the capture process, and designing the infrastructure needed to transport and store the captured CO_2. Process Integration along with its subset Heat Integration (HI) has proved to be an established approach for enhancing the efficiency of process, reduction of the resources consumption along with reduction of the emissions.[29] The process integration of carbon capture is a complex process that requires expertise in process engineering, capture technology, and infrastructure design. However, by integrating carbon capture into industrial processes and power generation, we can help in reducing greenhouse gas emissions along with mitigating the impact of environment change (Figure 4).

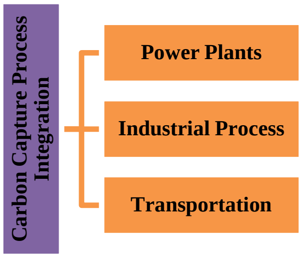

Figure 4. Carbon Capture Process Integration with different sources of carbon emissions

Power Plants - Being one of the primary generators of CO_2 emissions, power plants have the potential to substantially decrease the release of greenhouse gases through the implementation of carbon capture. This procedure entails removing CO_2 emissions from the power plant's exhaust gases and guaranteeing their secure storage.

Several carbon capture technologies, including oxy-fuel combustion, pre-combustion capture, and post-combustion capture, can be smoothly included into power plants. Important information about incorporating post-combustion carbon capture and storage into a pulverized coal-fired power plant is provided by Sanpasertparnich et.al.[30] The study made use of a simulation model to investigate the impact of the capture process on the operation, emissions, as well as power plants' costs. According to the study, the capture approach led to a significant decrease in CO_2 emissions even if it increased the cost of power production. The study does, however, have some serious flaws, such as its reliance on a simulation model and the absence of an assessment of the environmental implications of the capture process.[30] According to the research done by Owebor et.al.[31], a 450 MW integrated natural gas-fired combined cycle power station with carbon capture and storage (CCS) has undergone thermodynamic and environmental analysis. The research showed that the use of CCS technology significantly reduced CO_2 emissions, with an alleviation of 89.06% in the net CO_2 emissions from the power plant. Additionally, LCA analysis depicted a significant reduction in the environmental impact of power plant, with a decrease in the potential of the facility for causing acidification by 70.18% along with global warming by 76.55%.[31]

Industrial Processes - Significant environmental and financial benefits may result from the use of carbon capture technology into industrial processes. In addition to reducing greenhouse gas emissions and improving operational sustainability, it can help businesses achieve their emission reduction goals. Though it may necessitate a significant capital investment, complex technology, and adjustments to current practices, implementing carbon capture methods in industrial processes can be challenging. Therefore, it is substantial to carefully evaluate the practicality of carbon capture technology and any potential effects on industrial operations before putting them into use. A case study of a Swedish steel factory was used by Eliasson et.al.[32] to examine the effective heat integration of industrial CO_2 capture and district heating supply. In comparison to a non-integrated scenario, the study indicated that the optimal heat integration scenario lowered the energy penalty by 63% and the CO_2 emissions by 40%. Also found that the heat integration might enhance the economic performance of the CO_2 capture process, with a reduction of up to 15% in the cost of CO_2 capture.[32] Kuramochi et.al.[33] compared and assessed different carbon capture technologies that can be integrated into carbon-intensive industrial processes, including cement, chemicals, along with iron and steel. It is observed that that the oxy-fuel combustion technology has the highest energy penalty, while the chemical looping combustion technology has the lowest. The study also found that the economic performance of carbon capture technologies is heavily impacted by the energy cost, the CO_2 emissions cost, and carbon capture plant's capital cost.

Transportation - Carbon capture process integration through transport involves capturing CO_2 emissions from numerous transportation sources and storing them to prevent their release into the atmosphere. Carbon capture through transport is still a developing technology and faces some difficulties like high energy consumption, limited storage capacity, along with high costs. However, research in this area can help in the enhancement of efficiency and minimize the process cost, making it a feasible option for the reduction of CO_2 emissions from transportation sector.

Carbon Capture and Storage

Today, tackling global warming is a significant and urgent issue. Among the principal factors causing global warming is methane gas (CO_2) pollution from the combustion of fossil fuels, which must be significantly decreased to stay within the target range of a temperature of no more than 2°C. Fossil fuels, primarily coal, are the primary source of electricity production, and the energy industry continues to be one of the principal causes of CO_2 emissions.[34] The taking of and keeping of carbon (CCS) has received a fair amount of attention. Extensive discussion for a long time as a technological alternative that may substantially help achieve the goal of reducing GHG emissions. CCS entails capturing and storing emissions carbon dioxide produced by industrial sources or fuel-burning power plants. utilizing carbon dioxide for increased energy recovery or burying it below, like in deep saltwater aquifers or depleted gas and oil fields.[35,36] CCS, also known as sequestration and capture of carbon, is a technical advancement toward the production of sustainable energy. Carbon sequestration and sequestration refers to any method that can transfer carbon to a practical carbon sink while halting or reversing CO_2 emissions to the atmosphere (CCS). The method of storing CO_2 prior to getting released into the atmosphere is known as "CCS." atmosphere after being captured at its source.[37]

In order to separate the marketable methane from carbon dioxide present in gas fields, carbon capture and energy storage was first used in the 1920s. Early in the 1970s, CO_2 was captured at a Texas (USA) gas processing facility, piped to an oil field nearby, and afterwards injected into reservoir for improved recovery of oil.[38]

Today, the successful completion of several projects across the globe demonstrates the effectiveness of carbon capture and CCU technology. Another established method for lowering atmospheric carbon dioxide levels is the technology for sequestering CO_2 (such as carbon agriculture or urban forestry) (Figure 5). The primary disadvantage of CCS systems is their high CO_2 storage need. As a result, energy production and exploitation (Clinic) Technologies have been developed primarily to use CO_2 in different manufacturing procedures, but also to reduce air emissions. The idea of carbon capture is CO_2 also linked. , storage, and utilization (CCUS), a series of technologies designed to isolate Carbon dioxide from huge sources of emissions for conveying in such a condition, both for usage and for underground storage purposes, but also accompanied by CO_2 recycle.[39]

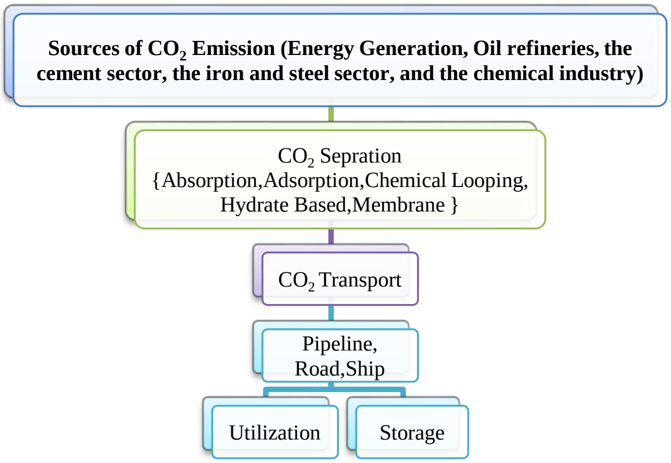

Figure 5. Carbon Capture and Storage Chain [39]

The CCS, CO_2 must first be extracted from energy and industrial sources before being transported to a site where it'll be permanently cut off from the atmosphere. Typically, CCS technology fall into one of three categories: post-combustion, oxyfuel combustion, and before to combustion. Absorb, adsorbent, electrochemical conversion burning, hydrate-based separation, membrane separation, as well as Cryogenic distillation, are different types of CO_2 separation technologies. Following its capture and separation, CO_2 is delivered (using everything from tanker trucks to ships & pipes) and may be stored in saltwater aquifers, deep ocean storage, oil and gas reservoirs, as well as unmineable coal beds. In contrast, if CO_2 could be recycled, it might be utilized as a solvent (for example, in oxidation processes), a chemical (for example, in mineral carbonation), and a fuel (for example, in biofuels made from microalgae) or in improved oil along with coal oil extraction (Figure 5).[39]

The primary goal of this endeavour is to use concentrated solar power to capture the CO_2 from coal-fired power facilities along with its atmosphere (CSP). After CO_2 has been captured, it is used to nurture microalgae in raceway ponds. Using mirrors or lenses, concentrating solar power (CSP) concentrates light illuminating a small region, creating warmth which might be taken into usage for energy production. CSP technologies occur in a range of forms, including Fresnel reflectors, dish Distillation system, solar energy towers, and parabolic troughs. Each of these methods focuses sun onto a receiver, which heats a fluid like water or molten salt, using various kinds of mirrors or lenses. In this study, sunlight is concentrated using Scheffler Dish technology.

Concentrating Solar Power

Even though the sun's beams emit a tremendous quantity of energy, their intensity is rather low when compared to that of other energy sources. The sun's rays must be concentrated to a greater level of intensity in order to be used for solar energy in a variety of applications.[40] Solar concentrators can help in this situation. Solar concentrators are machinery that gather and focus the sun's rays to create a stronger radiation beam. They function by concentrating sunlight into a small area, usually a receiver, using reflecting surfaces like mirrors or lenses. The focused radiation is absorbed by the receiver and transformed into heat, which has a number of uses. Solar concentrators come in a variety of designs, such as parabolic troughs,[41,42] as well as dish concentrators[41,43] and linear Fresnel reflectors. The main idea of all concentrators is to focus the sun's rays, yet each variety has its own distinct design and set of features. The heat generated by the solar concentrator can be utilized when a working fluid has been heated to the desired temperature, sun's rays have been focused onto the receiver. Freshwater, petroleum, or another fluid with the ability to absorb and store heat can be the working fluid.[44] After that, the warmth from working fluid can be utilized to drive turbine and other machinery to produce electricity, or it can be used directly for a variety of purposes like heating, heat water, or steam generating..

Scheffler Dish for Concentrating Solar Power

Wolfgang Sandel, a German physicist, invented the Scheffler dish in the 1980s, and it has subsequently been utilized for frying and other thermal purposes in many nations. In comparison to other solar concentrators, the dish has a number of benefits, including the capacity to monitor the heat and start concentrating solar radiation from a variety of angles. The Scheffler dish, a type of parabolic mirror, is used to direct sunlight toward the focal point (Figure 6). Applications that call for high-temperature heat, like culinary, water heating, steam production, and power generating, frequently use this kind of solar concentrator.[45,46]

Figure 6. Scheffler Dish Collector [47]

Sunlight is reflected and focused onto to the Scheffler dish's center of gravity must be function. To keep the dish directed directly at the sun, the dish is typically installed on a tracking device that moves with the sun. The dish is moved to quality assurance and control with the sun as it travels.[47–48] The receiver, which could be a liquid tube, a buffer layer, or another material that can absorb and store sun thermal radiation, which is heated at the Scheffler dish's focal point. The material's temperature rises as a result of the receiver's absorption of concentrated solar light. After then, the receiver's heat energy can be used for a number of uses.[49]

In order to generate chemical reactions that can be used to collect atmospheric carbon-di-oxide (CO_2) from the atmosphere, solar energy must be concentrated onto such a high-temperature material using a Collector Dish as just a solar concentrator. This is accomplished by heating a substance that can absorb and store CO_2 with concentrated sun light. In order to trap carbon using a Scheffler Dish, concentrated solar radiation is used to heat a substance to a high temperature, including such metal oxide or carbonate. The substance releases oxygen and absorbs CO_2 as a result. The resultant Hydrocarbon - rich substance is then delivered to a storage location in order to be kept in a secure location for a considerable amount of time. making use of CaO (CaO), sometimes referred to as quicklime, is such instance of a chemical process that may take place during this procedure. CaO combines with CO_2 to produce calcite ($CaCO_3$) and heat up when heated at a high temperature utilizing focused sun's rays from Scheffler Dish[50]:

$$CaO\ (calcium\ oxide) + CO_2(carbon\ dioxide) \rightarrow CaCO_3(calcium\ carbonate) + Heat$$

The generated $CaCO_3$ can be moved to a storage location and kept there for extended periods of time without risk. The Calcium chloride is subjected to high temperatures, which releases CO_2 and regenerates CaO to reuse in the process:

$$CaCO_3(calcium\ carbonate) + Heat \rightarrow CaO\ (calcium\ oxide) + CO_2(carbon\ dioxide)$$

The concentrated sun light from Scheffler Dish can potentially fuel this process. lowering the requirement for energy sources based on fossil fuels [50]. The Scheffler Dish method of carbon capture can also be utilized with these other metallic nanoparticles or silicates, such as magnesium (Feo(oh) or potassium carbonate ($Li2CO_3$).[17] The substance used and the circumstances surrounding the reaction will determine the precise chemical reactions that take place. An environmentally friendly energy source might be created by using the Collector Dishes as a concentrator in the carbon capture process to power chemical reactions that absorb CO_2 from the atmosphere.

Stirling dish for Concentrating Solar Power

Stirling dish is a sort of solar concentrator and is the main focus of the process of solar energy conversion. The energy can subsequently be put to use in a variety of ways, including as powering chemical reactions that absorb carbon[51] or producing electricity. The Synchronous motor is a heat exchanger that works by repeatedly compressing and expanding a gas at various temperatures, usually helium. The engine is situated at the parabolic dish's focal point, where it is exposed to concentrated solar radiation. The air expands and pushes a piston as a result of the engine absorbing heat from sun radiation.[52] This produces mechanical energy. The third kind of solar heat system, which consists of, dish-engine systems, to produce power, at the focal point of the dish are a complex parabolic concentration, heat sensor, and heat engine/generator.[53] Dish-Stirling systems track the sun, capturing the energy it generates, and sending it to a steam generator or generator through a hollow receiver (Figure 7).

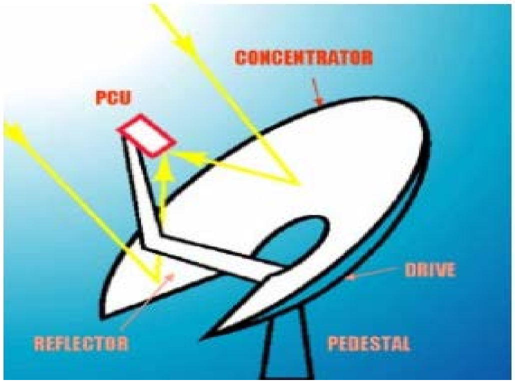

Figure 7. Dish Stirling system components [54]

This mechanical power can then be applied to drive chemical changes for carbon capture or a generator to generate power. The Stirling engine utilizes the high-temperature heat energy it has gathered to create mechanical energy, which is then transformed into electricity by an electric generator. Casserole system get the lowest commercial penetration when contrasted to other CSP technologies, while having the highest geometric concentration ratios and solar-to-electric conversion efficiencies.[55] The high cost of installation both the challenge of linking such devices to methods for thermal storage are primarily what restrict the profitability of dish-Stirling systems. It is feasible to enhance energy generation while also providing a considerable environmental benefit through reduced CO_2 equivalent emissions.

Carbon Capture asnd Storage (CCS) Technologies

It is conceivable capture dioxide (CO_2) outputs from industrial operations, such as electricity production, as well as them for quite some time in rock formations deep underground. This method is known as the capture and storage of carbon (CCS). CCS seeks to lessen atmospheric CO_2 emissions, which are a significant cause of climate change and global warming [56]. Yet because CCS remains a relatively new technology, there are a number of technical, financial, as well as legal issues which need to be resolved before it can be scaled up and made affordable. Depending on the origin of Emission and the storage location, different strategies are utilized in the capture and storage of carbon (CCS).

Post-combustion recording this method extracts CO_2 off flue gases released by power plants. Industrial facilities and plants. A solution is employed to soak up CO_2 from flue gases in amine scrubbing, which is the most applied post-combustion capture technology, globally (Figure 8). Zhao et.al.[57] discussed preparation methods, takes into account the structure-performance relationship when utilizing carbons to absorb CO_2, and reviews current developments in the PCC-specific use of carbons for CO_2 capture. Fernandez et.al.[58] used the life cycle analysis approach to assess the a three coal's impact on the environment combustion fueled energy supply networks from cradle to grave, with as well as without carbon storage and capture (CCS). The results reveal that CCS significantly lowers Gas (emissions (ghg) every watt to 243 g/kWh. Relative to the semi and critical levels, this represents a 78 and 71% reduction. Contemporary power plant. Using an accurate, fully integrated model, the business agility of super coal-fired CO_2 capture using an amine-based method is assessed in power plants. The energy output penalty, for example, drops between 458 kilowatt hour (without traditional third - party integrations) to 345 kilowatt hour (with advance integration options) at 50% energy intake and 90% capture, as opposed to a drop of 361 kilowatt hour assuming 100% gasoline consumption and 90% capture, to 342 kWh/tCO_2.[59] A thorough parametric research for inter membrane systems utilized in coal-fired power plants is described by Li Zhao et.al.[60] Depending on an optimum gasifier mixture of 14 wt percent CO_2 and 86 mol% N_2 that use the Non - revenue water reference power plant, a cascade membranes system exhibits a modest energy advantage over MEA absorption.

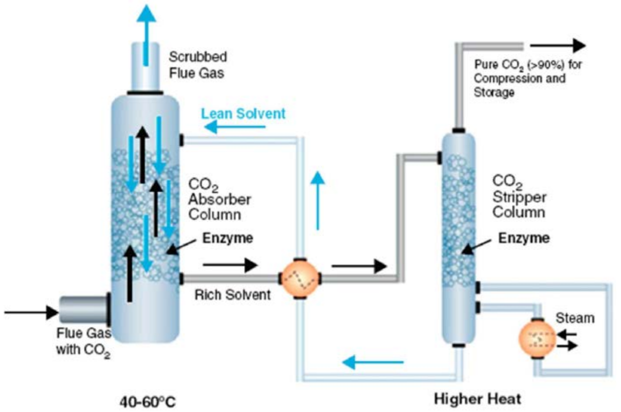

Figure 8. Post-Combustion Carbon Capture Process [74]

Pre-combustion capture: This method reforms fossil fuels like natural gas to catch CO_2 before it is discharged into the atmosphere. The gas is employed in energy production or other industrial activities after the hydrogen gas and CO_2 from the reforming process are separated (Figure 9). To increase the effectiveness and reduce costs of which was before Carbon capture method. A broad range of operating configurations were techno-economically evaluated using the Alpine Plus commercial process simulator based on chemical absorption with the utilisation of [P2228][CNPyr] ionic liquid.[62] If only direct expenses were taken into account, the lowest cost attained for next generation solvents could even be lower than the 40 \$/tCO_2 objective.[62] This was based on an IL scaling prices up of 50 \$/kg. For the hydrates project. A project separation of atmospheric CO_2 from of the Carbon dioxide (fuel gas) gas mixture, sand or silica gel are the medium in a cylinder with a fixed bed.[63] Both the speed of hydrate formation and the pace at which liquids become hydrates are rapid. Using stable state tests, gas absorption measurements, and microscopic studies, the viability of the drink plenty of fluids which was before capture for atmospheric CO_2 if there isn't one thermal silica gels with pores and activator were investigated in [64]. In every case, concentrations more than 90% were attained in the hydrate phase.

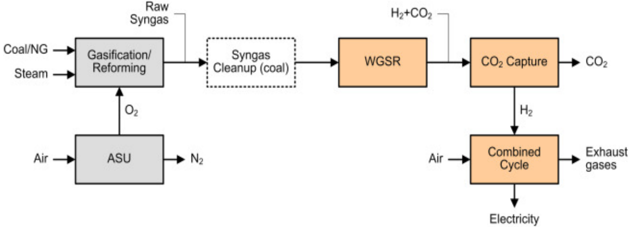

Figure 9. Pre-combustion Carbon Capture [73]

Oxy-fuel combustion: This process burns carbon fuels in pure instead of air, oxygen, producing in exhaust gases that is primarily made up of water and CO_2 vapor. After that, the CO_2 can be collected and kept. Although there are currently small-scale renewable energy generation options on the market, the expense of lowering carbon dioxide emissions by renewable energy has currently been very high.[65] When compared to Oxygen-fuel combustion and post-combustion capture can both lower global warming by 0.00047 mPET2000, acidification by 0.04084 mPET2000, eutrophication by 0.04486 mPET2000, photochemical ozone generation by 0.001 mPET2000, and slag and ashes by 0.35082 mPET2000.[66] For the purpose of converting a 550 MWe coal-fired power station to oxyfuel combustion, research was conducted to evaluate various oxygen generating systems.[72] Combining oxygen transport membranes and electrolysis produces the greatest results, using 59.31% less energy than cryogenic distillation. The overall energy penalty is thus reduced to 7.56% points. At 51.48 dollars per megawatt hour (MWh), the oxygen transport membrane also offers the lowest cost of power in retrofitting scenarios. For the two techniques, the costs of saved CO2 are 31.79 and 34.15 dollars per ton of CO_2.

Direct air capture: Using chemical processes like adsorb, absorption, or membrane separation, this method directly takes CO_2 from the air (Figure 10). The investigation of the public contracts of CO_2 DAC is made in [67]. Based on complete hourly modeling for the Maghreb region, (LCOD) in high-resolution space. The main findings include an estimated LCOD of 55 €/tCO2 in 2050 with just an additional cost reduction reaction of up to 50%. Today, chemisorption is used by the majority of direct flight capture (DAC) adsorbents, including amines. Finding substances with weaker, reversible adsorption, however, might increase these adsorbents' regenerability. Alcohol exposure In accordance with more accurate carbon dioxide and water temperature of absorbed and adsorption isotherms, as well as GaPO adsorbents are not apt for DAC applications, it has been estimated.[68] The technology known as direct air capture (DAC), which produces no carbon emissions, has drawn a lot of interest as a capable tool for combating climate change. Traditional DAC adsorbents' outstanding problems and potential advancements. There are examples of CO_2 capture.[69] The strong CO_2 adsorption capability, great regenerability, and simplicity of scaling up make new Ships solid ammonia materials for DAC promising.

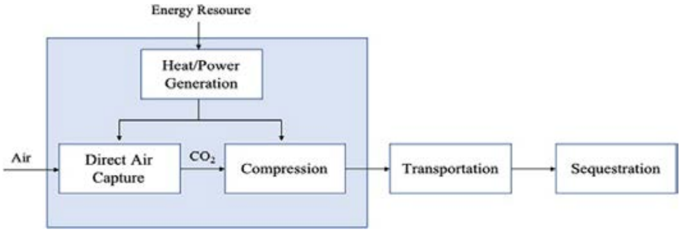

Figure 10. Direct Air Capture Technique [*70*]

Generally, CCS is a developing technology, and new methods and strategies are being created to increase its efficiency and scalability. The analysis provided by McQueen et.al.[70] assesses the price of combining a Direct Air Capture (DAC) method based on solvents with various energy systems. For the purpose of capturing 1 Million Tons Carbon dioxide per year, it contrasts eight energy systems paired with two DAC designs. The findings demonstrate that the entire capture cost, which ranges from one hundred fifty dollars to six hundred ninety dollars per ton of CO2 captured, depends on the specific kind of energy system and power costs. In work by Mariliis et.al.[71], two techniques for removing carbon dioxide are compared: BECCS and DACCS. BECCS is more cost-effective in capturing CO2, but DACCS has lower system costs overall because of its flexibility in power generation. The study places a strong emphasis on taking broader system effects into account rather than making decisions purely based on LCOC.

METHODOLOGY

For a number of reasons, collecting CO_2 from tar power plants is crucial. Coal-fired power plants are one of the main sources of greenhouse gas emissions. Stations, and trapping CO_2 can assist to lessen the harm that these emissions do to the environment. In the setting of worldwide climate change, where lowering emissions of greenhouse gases is a top concern, this is especially significant. It is possible to enhance air quality and lessen the negative impacts of global warming, like increasing sea levels, an increase in the occurrence of severe thunderstorms, as well as a shift in the distribution of species of vegetation and animals, by capturing CO_2 from tar power plants. Since the fact that plants may capture CO_2 for a variety of commercial uses, including the production of chemicals, building materials, and better oil recovery, plants can also have financial advantages. With the aid of these applications, new markets and avenues for innovation may be opened up, stimulating economic growth and employment creation. This work's primary goal is to present a way for extracting CO_2 from coal-fired power stations and its air using concentrated solar power. Two methods of employing CSP devices to reduce atmospheric carbon dioxide have been addressed in this paper (Scheffler dish and Stirling dish).

Methodology for Capturing from Coal-Fired Power Plants of CO2 using Scheffler dish

The Collector dish is a kind of solar collector that directs light onto a sensor using mirrors. When CO_2 is being captured, the receiver is covered with a substance that absorbs CO_2, enabling the intense sunlight to produce heat and power the Carbon capture process. The receiver material throughout the CO_2 cycle, interacts to CO_2 in the air capture process, capturing the fuel and turning it into a solid. High temperatures are required for this reaction, usually between 600 and 800 °C. The solid substance is moved to a different vessel for regeneration after the CO_2 has indeed been captured. High temperatures are applied to the vessel, which regenerates the material and releases the CO_2 that has been trapped, preparing it for another cycle of CO_2 absorption. The CO_2 is subsequently transported to a storage place, such as a rock structures or another long-term storage facility, after being compressed. By storing the CO_2, it is kept out of the air, where it would otherwise cause warming.

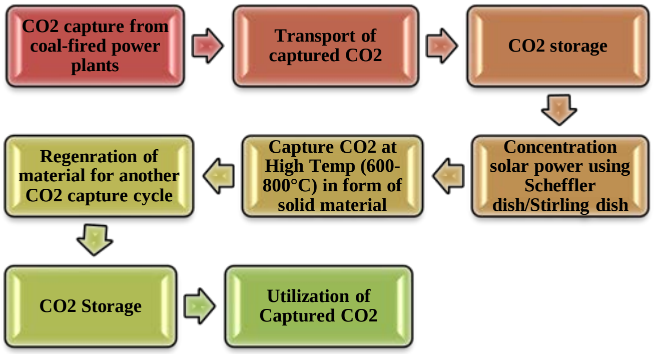

Figure 11. Flowchart for CO_2 Capture from Coal-Fired Power Plants using Scheffler dish/ Stirling dish as CSP

Also, the collected CO_2 can be applied to a number of manufacturing applications, such as improved recovery of oil, in which it is pumped in oil reservoirs to raise pressure and speed up oil extraction. Flow chart for the complete process is given in Figure 11. It can also be used to make other items like chemicals or building materials. All things considered, using the Scheffler dish to focus sunlight and collect CO_2 is a potential means for minimizing greenhouse gas emissions as well as tackling climate change.

Methodology for Capturing CO_2 from Coal-Fired Power Plants using Stirling dish

The CO_2 capture process occurs at high temperatures, typically around 600-800°C. The After that, solid material is moved to a different vessel for regeneration. The vessel is heated to a high temperature, which releases the captured CO_2 and regenerates the material, making it ready for another cycle of CO_2 capture. The captured CO_2 is then compressed as well as transmitted to a storage location, such as a geological formation or other long-term storage facility. Utilizing Stirling dish as CSP to capture CO_2 in coal-fired power plants has several advantages. For one, it is a renewable and sustainable energy source that does not emit greenhouse gases. Additionally, CO_2 may be extracted from a number of sources using it, such as power plants and industrial processes.

However, there a sturdy substance, High temperatures, usually between 600 and 800 °C, are involved in the CO_2 capture process. After that, the solid substance is moved to a different vessel for regeneration. The material is regenerated and the container is warmed to a high temp, which releases the CO_2 that has been trapped and makes it prepared for yet another round of CO_2 collection. The CO_2 is subsequently transported to a storage place, including a geological formation or another long-term storage facility, after being compressed.

There are various benefits of employing Stirling dishes as CSP for coal-fired power plant CO_2 capture. It is a greenhouse gas-free, sustainable, and renewable energy source, for starters. It additionally has the potential to increase the solubility from a number of sources, such as factories and power plants.

Although, there are several drawbacks to this technique as well, including as high startup and operating expenses, the need for expansive land areas to deploy The dishes, and the requirement for intensive upkeep to maintain the dishes functioning properly. Notwithstanding these difficulties, Stirling dish CSP has the ability to be a significant contributor to the decrease in emissions of greenhouse gases and the promotion of renewable energy sources.

CSP can be utilized to capture CO_2 in coal-fired power stations using both Stirling and Scheffler dishes. The two approaches do differ in a few ways, though. The Frankfurt plate is a parabola dish that directs sunlight onto a receiver, which powers an electric Stirling engine. This technique involves coating the receiver with a CO_2 adsorbent substance, and the Carbon capture process is heated by sunlight to a high temperature. The CO_2 that is caught can be kept or utilised in factories. The Scheffler dish, on the opposite hand, is a mirror that directs sunshine onto a receiver covered in a CO_2 adsorbent substance. The CO_2 collection mechanism is fueled by the heat produced by the intense sunshine. The seized CO_2 is then delivered to a storage facility after being compressed. In terms of effectiveness, the Stirling dish outperforms the Scheffler dish when energy is transformed into electricity. The Scheffler dish, on contrary, has proved to be more suitable for CO_2 applications since it has a bigger reflective surface and therefore can focus sunshine onto a larger receiver. In conclusion, both the Stirling dish and the Collector dish can be utilized for capturing CO_2 off coal-fired power stations using CSP. Table 4 shows that the decision between the two approaches will be based on the project's size, cost, and desired efficiency.

Compared to Stirling dish technology, Collector dish technology is easier to use and less expensive, making it more practical for small power stations or developing nations. Another benefit of scheffler dishes is that they may collect carbon dioxide (CO_2) from the atmosphere as well as from power plants. This means that a range of sources, such as industrial activities and transportation, can be captured using Scheffler dishes. Collector dish technology can also be utilized for other purposes, including dining or heat water, which can be advantageous for communities in various ways.

Stirling and Scheffler dishes are both used for sunlight concentration. When it comes to absorbing CO_2 through coal-fired power plants, electricity systems have several drawbacks. The Kerr dish CSP system has the drawback of requiring a lot of dishes to produce the required output power, which can be costly and take up a great deal of room. A Stirling engine can also be complicated and need frequent maintenance, which increases operating expenses. The Sandel dish CSP system, on the opposite hand, necessitates a sizable quantity of room for the dishes, which might be problematic in regions with a shortage of suitable land.

Table 4. Criteria, Stirling Dish of Scheffler Dish

Criteria	Stirling Dish	Scheffler Dish
Technology type	Thermal-kinetic	Thermal-only
Concentration method	Parabolic dish shape	Parabolic shape
Tracking system	Dual-axis solar	Single-axis solar
Size	Typically has a diameter of 7-10 meters	Can have a diameter of up to 16 meters
Energy conversion efficiency	30-40%	30-60%
Optimal working temperature	800K	500K
Focal point temperature	1700K	800K
Power output per unit area	8-25 kW/m²	3-5 kW/m²
Thermal energy storage	Optional	Optional
Operating temperature range	600-1200K	400-800K
Maintenance	Moderate-High	Low-Moderate
Applicable location	Sunny areas with high DNI	Sunny areas with moderate DNI
Cost	Expensive	Inexpensive
Applications	Primarily used for electricity generation	can be applied to a range of activities, comprising of culinary, heating, as well as industrial ones.

Note: The amount of solar energy that strikes a ground that is normal to the sun per units area per unit time is known as direct normal irradiance, or DNI.

Maintaining optimal attention also needs careful monitoring of the sunlight throughout the day, which can be challenging in regions with unpredictable weather. At last, the high temperatures needed for the CO_2 collection process can put a lot of strain on the receiver's components, necessitating regular replacement and driving up maintenance expenses

CHALLENGES AND FUTURE DIRECTIONS IN CARBON CAPTURE

In order to reduce carbon emissions, Carbon Capture and Storage (CCS) technology must be widely used. However, as seen in the Figure 12, its widespread application confronts substantial difficulties.

Scale-up and Deployment- Although carbon capture technologies have a tremendous deal of potential for reducing greenhouse gas emissions, large-scale implementation of these systems presents various difficulties. The expense of the present carbon capture devices is one of the main obstacles because it can render them unprofitable in some areas.[86-90] A significant barrier can be the requirement for large infrastructure investment necessary to scale up these technologies to industrial levels. Other difficulties include cutting back on energy use, enhancing the selectivity of capturing systems, and lowering environmental effects. The development of more efficient and affordable technology is necessary, as is the encouragement and promotion of the use of carbon capture systems through governmental initiatives and market mechanisms. When deciding which CCUS techniques are best, considerations including location, time frame, money, and prospective applications in the future must be carefully considered.[75] The focus of research should be to develop technologies which are easy to integrate into existing industrial processes and might be used in a variety of applications. Close collaboration between industries, governments, academia, as well as public awareness and support, will be necessary for the successful adoption of these technologies.

Policy and Regulatory Frameworks - Lack of comprehensive policy and regulatory frameworks is one of the biggest obstacles to the adoption of carbon capture systems. Despite the fact that many nations have set goals for lowering their carbon emissions, there still needs to be clear legislation and financial incentives for encouraging the application and growth of carbon capture systems.[81-85] For example, tourism, FDI, and industry have all contributed to environmental deterioration in African nations with rapid economic expansion, particularly the 27 countries analyzed.[76] Effective policymaking and CO_2 reduction depend on political stability. Improved governance improves the quality of the environment and livelihoods. It is crucial to coordinate actions with UNFCCC regulations. Strategies for reducing pollution and intergovernmental collaboration are advised.

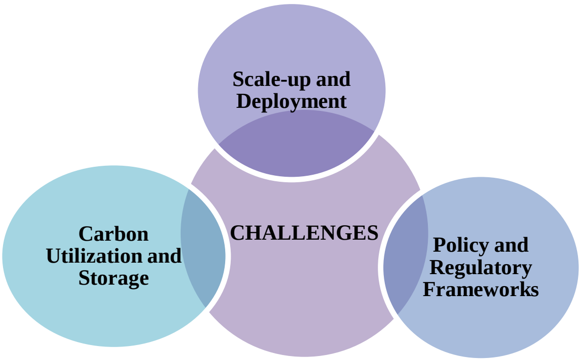

Figure 12. Challenges of Carbon Capture Techniques

Carbon Utilization and Storage - Although it is a crucial step in the fight against climate change, carbon capture is not a complete solution. It's essential to use or store carbon that has been captured in a secure way. Utilizing collected carbon to create value-added goods like building materials, chemicals, and fuels is one strategy that shows promise.[78-80] This method has economic advantages in addition to helping to lower carbon emissions. Utilizing carbon does present certain difficulties, though, such as the necessity for affordable infrastructure and technology, as well as the requirement for market incentives and supportive regulations.[91-95] Another strategy involves storing collected carbon by injecting it into geological formations such deep geological formations,[96] saline formations,[97] and depleted oil[98] and gas reservoirs.[99] The effectiveness and safety of the storage need to be ensured with the use of this method that necessitates careful site selection, monitoring, and verification.[101,102] For example, the study conducted by Chen et.al.[77] identified issues that could prevent the adoption of CCUS, such as inadequate geologic storage capacity investigation. The years 2040 to 2060 are anticipated to be the "Golden Age" for the global deployment of CCUS. Resolving regulatory shortcomings and improving financial support are among the recommendations. Additional study is necessary for the establishment of regulatory frameworks that ensure the security and long-term viability of carbon utilization and storage technologies, as well as for the development and optimization of these systems.

CONCLUSION

This study focuses on carbon capture and storage (CCS) technologies along with their capability of reducing carbon dioxide (CO_2) emissions to combat climate change. It offers a framework of current CCS techniques, materials, and their feasibility for large-scale deployment. The study also discusses the challenges and future directions of CCS, including scaling up the technology, developing supportive policies and regulations, and exploring new avenues for carbon utilization and storage. Furthermore, the study examines the use of CCS for capturing and storing coal emissions to reduce the adverse impacts of global warming and CO_2 emissions. Various CCS methods, such as CO_2 separation, transport, and storage options like coal ash storage and deep ocean storage, are outlined. The study also explores the potential of solar thermal power (CSP) systems, specifically the Stirling and Scheffler dish technologies, in absorbing CO_2 from the atmosphere and coal-fired power plants. Despite limitations, the Scheffler dish technology stands out as a widely available and adaptable option, making it desirable for small power plants and developing nations. Implementing CCS and CSP is recognized as a crucial step in generating clean energy and lowering greenhouse gas emissions. Overall, the study highlights significant progress in carbon capture technologies while emphasizing the need for ongoing research and innovation for addressing the challenges along with full utilization of the potential of CCS in mitigating climate change.

CONFLICT OF INTEREST

There is no conflict of interest as this research was conducted with complete impartiality and without any external influences that could potentially affect the integrity of the findings or interpretation of the results.

ACKNOWLEDGMENT

Authors acknowledge the reviewers for their constructive feedback.

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