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Assessing the Effectiveness and Sustainability of Carbon Capture and Storage (CCS) Technologies for Mitigating Greenhouse Gas Emissions

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Abstract: Carbon Capture and Storage (CCS) technologies represent a pivotal frontier in the battle against climate change, offering innovative solutions for mitigating greenhouse gas emissions. This comprehensive review explores the multifaceted landscape of CCS, delving into its essence, diverse technological approaches, and real-world implications. It investigates the effectiveness of CCS across various emission sources, scrutinizes the environmental ramifications, evaluates economic feasibility, and probes the sustainability of long-term carbon storage. Furthermore, it scrutinizes the intricate web of policies and regulations shaping CCS adoption and dissects the formidable challenges that must be surmounted. Through a tapestry of case studies, this review illuminates the practicality of CCS applications. As we gaze into the future, emerging technologies and evolving research avenues beckon, promising an enduring role for CCS in the global endeavor to attain climate stability. Ultimately, CCS emerges not merely as a tool but as a critical pillar in our collective effort to safeguard the planet for generations to come.

Index Terms: Carbon Capture and Storage, CO2 emissions reduction, Climate change mitigation, Economic feasibility, Policy framework, Long-term carbon storage

1 INTRODUCTION

Climate change is one of the most pressing challenges facing humanity today. The burning of fossil fuels is the primary source of greenhouse gas emissions, which are driving climate change. Carbon capture and storage (CCS) is a promising technology for mitigating greenhouse gas emissions from industrial processes and power generation [1].

Carbon capture and storage (CCS) represents a method for mitigating carbon emissions, potentially playing a pivotal role in addressing the issue of global warming. CCS encompasses the process of trapping carbon dioxide (CO2) emissions generated by industrial activities like steel and cement manufacturing or the combustion of fossil fuels in electricity generation. Afterward, this captured carbon is transported from its source, either by ship or through pipelines, and securely stored deep beneath the Earth's surface in geological formations [2].

CCS technologies can capture and store a large portion of global CO2 emissions, making them a significant technology for addressing climate change. CCS technologies are also complementary to other climate change mitigation strategies, such as renewable energy and energy efficiency. However, there are still a number of challenges that need to be addressed before CCS technologies can be widely deployed. The cost of CCS technologies is still relatively high, and there is a need for more public and private investment in CCS research and development. There is also a need for clear and supportive government policies for CCS, and for public awareness and acceptance of CCS technologies. Despite these challenges, CCS technologies are an important part of the solution to climate change. This research paper will assess the effectiveness and sustainability of CCS technologies for mitigating greenhouse gas emissions. The paper will discuss the different types of CCS technologies, the challenges to their deployment, and the potential benefits of CCS for climate change mitigation [3].

Carbon capture and storage (CCS) is a set of technologies that can be used to capture carbon dioxide (CO2) emissions from industrial processes and power generation, and then store them underground in geological formations. CCS is one of the most promising technologies for mitigating greenhouse gas emissions and combating climate change.CO2 is a greenhouse gas that traps heat in the atmosphere. When CO2 is emitted from industrial processes and power generation, it contributes to climate change. CCS technologies can help to reduce these emissions by capturing CO2 and storing it underground, where it cannot escape into the atmosphere [4].

CCS technologies work in three steps:

1. Capture: CO2 emissions are captured from the source, such as a power plant or industrial facility.
2. Transport: The captured CO2 is transported to a storage site. This can be done via pipeline or ship.
3. Storage: The CO2 is injected into a geological formation, such as a saline aquifer or depleted oil and gas reservoir.

CCS technologies are still in their early stages of development, but they have the potential to play a significant role in reducing global CO2 emissions. The Intergovernmental Panel on Climate Change (IPCC) estimates that CCS could contribute to reducing global CO2 emissions by 20-55% by 2050. CCS is a significant technology for addressing climate change because it has the potential to capture and store a large portion of global CO2 emissions. CCS technologies can be used to reduce emissions from a variety of sources, including power plants, industrial processes, and natural gas processing. CCS is also a complementary technology to other climate change mitigation strategies, such as renewable energy and energy efficiency. CCS can help to reduce emissions from sectors where it is difficult or impossible to reduce emissions through other means, such as heavy industry and cement production [5].

2 TYPES OF CCS TECHNOLOGIES

Carbon capture and storage (CCS) is an approach aimed at trapping the highly concentrated carbon dioxide (CO2) found in the exhaust gases of fossil fuel-driven power plants and other emission sources and centralizing it for storage. Three distinct techniques exist for capturing CO2: pre-combustion CO2 capture, post-combustion CO2 capture, and the oxy-combustion CO2 capture method.

1. Pre-combustion carbon capture involves capturing carbon dioxide (CO2) before combustion occurs, typically achieved through fuel gasification with oxygen. An example is the integrated IGCC (Integrated Gasification Combined Cycle) coal gasification technology.
2. On the other hand, post-combustion carbon capture occurs after the combustion process, where CO2 is captured from the flue gas. This can be achieved through chemical absorption, physical adsorption, membrane separation, or a chemical loop.
3. Oxy-combustion carbon capture occurs after combustion within an oxygen-rich atmosphere, with CO2 separation occurring during the oxy-combustion process. This approach often involves the use of an oxygen gas turbine. The oxygen-rich atmosphere is typically created by removing nitrogen from the air before combustion [6].

2.1 Pre-combustion capture

Pre-combustion carbon capture involves a fuel reacting with oxygen, air, or steam to produce a mixture known as 'synthesis gas (syngas)' or 'fuel gas,' consisting mainly of carbon monoxide and hydrogen. Subsequently, carbon monoxide undergoes a reaction with steam in a catalytic reactor called a 'shift converter,' resulting in CO2 and additional hydrogen formation. CO2 is then separated from this mixture, typically using physical or chemical absorption methods. This separation yields a hydrogen-rich fuel suitable for various applications, including boilers, furnaces, gas turbines, engines, and fuel cells. These systems hold significant strategic importance [7]. Industries often employ chemical absorbents like carbonates and physical solvents like polypropylene glycol and methanol for capturing CO2 from processed syngas. The calcium looping process also offers a cost-effective approach to pre-combustion CO2 capture. This method involves the sorption of Cao with CO2 and the subsequent desorption of CaCO3 to release CO2 at an optimal temperature [6]. Fig. 1 illustrates pre-combustion CO2 capture method

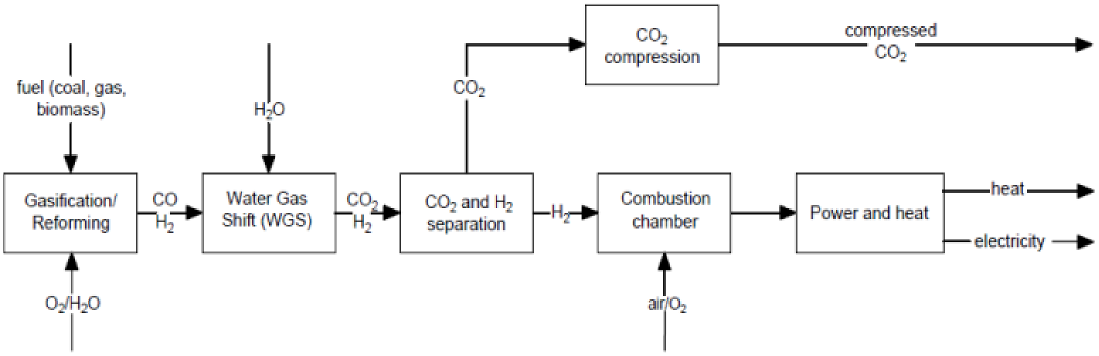

Fig.1. pre-combustion CO2 capture method [6]

2.2 Post-Combustion CO2 Capture

The fundamental concept behind post-combustion capture involves the extraction of CO2 from flue gases. In a standard coal-fired power generation setup, the process begins with fuel combustion using air in a boiler to create steam, which drives a turbine for electricity generation. The resulting exhaust from the boiler, known as flue gas, primarily contains nitrogen (N2) and carbon dioxide (CO2). Post-combustion capture is considered the most advanced and effective technology for capturing CO2 emissions, particularly in the context of coal-fired power plants [8]. In contemporary carbon capture processes in numerous power plants, an absorption technique utilizing chemical solvents like amines is frequently utilized. The procedure involves lowering the temperature of the hot flue gas to a range of 40 to 60 °C before introducing it into the absorber, where CO2 forms bonds with the chemical solvent. Subsequently, the CO2-rich solvent is transferred to a stripper unit, where the solvent undergoes heating to enable solvent regeneration within the temperature range of 100 to 140 °C, and this process strips off the CO2. The operation involves several energy-intensive components such as pumps, blowers, compressors, and heating, which reduce overall process efficiency [9].

Methods currently used for CO2 separation include the following:

I. Physical and chemical solvents, particularly monoethanolamide (MEA)
II. Various types of membranes
III. Adsorption onto solids
IV. Cryogenic separation [10].

Absorption: Solvent scrubbing is a well-established carbon dioxide (CO2) capture system widely employed in industries such as chemicals and oil. It relies on a chemical solvent that reacts with CO2 in the flue gas and can be regenerated at higher temperatures, resulting in a purified CO2 stream suitable for compression and subsequent storage. The exhaust gas is cooled and treated to eliminate particulates and other contaminants before entering the absorption column. Inside the absorption column, the amine solvent engages in a chemical reaction with CO2, leading to absorption. The CO2-rich solution then proceeds to a stripper column where the temperature is elevated (typically to around 120°C) to release the captured CO2. Subsequently, the liberated CO2 is compressed, while the regenerated absorbent solution is recycled back to the stripper column for further use [8].

Membranes: Membrane-based gas separation exploits differences in physical or chemical interactions between gases. The membrane material is engineered to facilitate the faster passage of one gas component over another to achieve the carbon capture process. These membrane modules can serve in two primary capacities: conventional membrane separation units or gas absorption columns. In the former scenario, the removal of CO2 occurs thanks to the inherent selectivity of the membrane, which discriminates between CO2 and other gases involved in the process. In contrast, in the latter case, CO2 removal is achieved through gas absorption, where typically microporous, hydrophobic, and nonselective membranes function as a fixed interface for CO2 transfer. This approach to gas separation utilizing membranes is relatively recent, characterized by lower selectivity and higher energy consumption [8].

Adsorption: Adsorption involves the adherence of molecules to a surface, while absorption entails the incorporation of molecules into a material. In the context of CO2 capture in power plants, the setup and equipment for adsorption and absorption are similar, requiring a regeneration step for the capture medium. The primary advantage of employing adsorption over absorption for CO2 capture lies in the reduced heat energy needed for regenerating CO2. The adsorption process is currently in the developmental stage, with various adsorbent materials being explored. Examples of these materials include zeolites and metallic organic frameworks [11].

Cryogenics: This process uses a principle of separation based on cooling and condensation. This method is applied to CO2 capture, where the gas stream contains high CO2 concentrations. It is presently not applied to more dilute CO2 streams like those encountered with typical power generation plants. This technique also requires significant amounts of energy for separation [8]. Fig.2. shows Post-Combustion CO2 capture method.

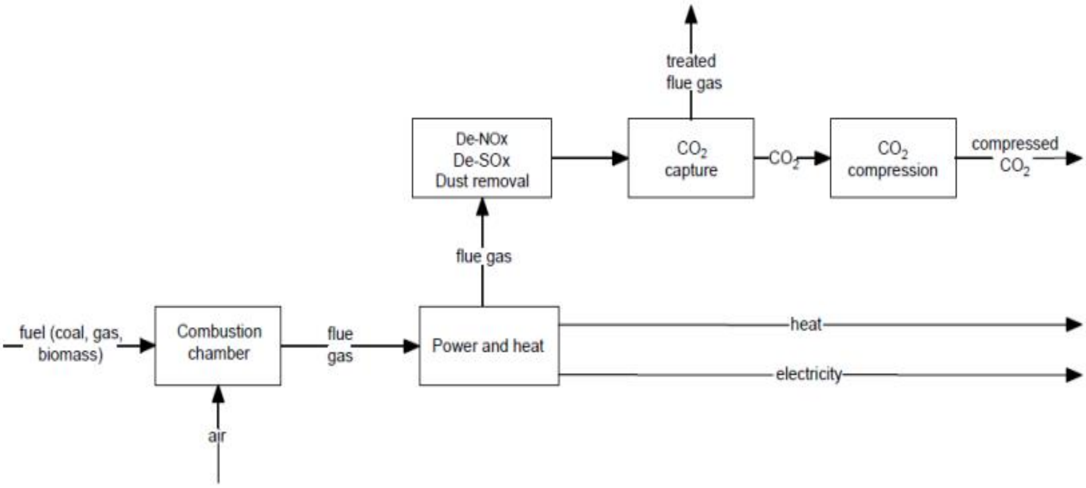

Fig.2. Post-Combustion CO2 capture method [6]

2.3 Oxy-fuel combustion capture

One of the techniques used for capturing CO2 from power plants is oxy-fuel combustion capture. In short, this technology aims to increase the CO2 concentration in the flue gases by reducing the N2 in the gas used for combustion [11]. Oxy-fuel combustion is a process in which coal combustion occurs in an oxygen-enriched (i.e., nitrogen-depleted) environment, thereby producing a flue gas comprised mainly of CO2 (up to 89vol.%) and water. The water is easily separated, and the CO2 is ready for sequestration [10]. Fig.3. shows combustion CO2 capture method

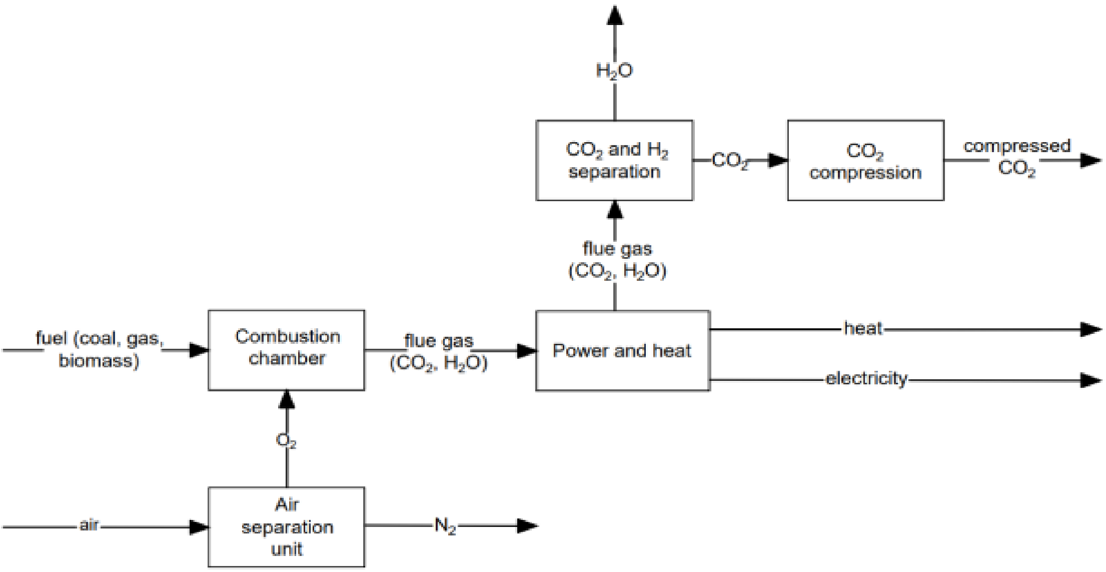

Fig.3. combustion CO2 capture method [6]

3 EFFECTIVENESS IN REDUCING CO_2 EMISSIONS

The global imperative to mitigate climate change and reduce greenhouse gas emissions has prompted the development and deployment of various carbon capture and storage (CCS) technologies. These innovative solutions aim to capture carbon dioxide (CO_2) emissions from industrial processes and power generation facilities, preventing their release into the atmosphere and thereby curbing their contribution to global warming. CCS technologies come in various forms, each with its own set of advantages and challenges. This part explores the effectiveness of three primary CCS approaches: pre-combustion, post-combustion, and oxy-fuel combustion.

3.1 Post-Combustion

The effectiveness of CO_2 post-combustion technology is underscored by a series of compelling advantages that make it a cornerstone in the quest for greenhouse gas reduction. Firstly, it stands out as one of the most easily applicable technologies for existing sources of emissions, demonstrating its adaptability to a wide range of industrial settings. This characteristic is precious when considering its implementation in existing power plants after retrofitting, where it effectively reduces the density of greenhouse gases without requiring radical changes to the underlying combustion technologies. Furthermore, the maintenance of post-combustion capture systems can be seamlessly integrated into plant operations, eliminating the need for shutdowns and offering precise control over the capture process. Notably, post-combustion capture technology boasts higher thermal efficiency when converting emissions to electricity, making it an attractive option for energy-intensive industries. Its compatibility with retrofitted combustion technologies and environmentally friendly adsorbents, such as activated carbon, further enhance its appeal as a green and economical solution. Most significantly, the versatility of post-combustion technologies extends to their application across various industrial sectors, from power generation to cement and iron and steel production. This wide-ranging adaptability positions post-combustion technologies as a potent and immediate contributor to the reduction of CO2 emissions, firmly establishing them as a critical player in pursuing a sustainable, low-carbon future [12].

The effectiveness of CO_2 post-combustion, while promising in its mission to reduce carbon emissions, has its share of challenges. One key hurdle lies in developing efficient adsorbents, particularly dry capture methods, to enhance cost-effectiveness and energy efficiency. Moreover, the limited availability of an ideal sorbent for post-combustion CO_2 capture poses a considerable constraint. Another drawback is the additional energy required for compressing the captured CO_2 and the need for treating high gas volumes, given the low partial pressure and concentration of carbon dioxide in the flue gas. Regenerating sorbents, such as amine solvents, also demands substantial energy resources. Furthermore, developing suitable OMS (adsorbent) materials is imperative to optimize the process. In post-combustion CO_2 capture, gas mixtures primarily consist of CO_2/H_2 and CO_2/N_2, with the inevitable presence of other secondary species that can significantly affect separation even in dilute concentrations, necessitating pretreatment of the flue gas. The operation at low temperatures limits the choice of suitable solid adsorbents, with activated carbon and zeolites being the primary options for low-temperature applications. Lastly, capturing CO_2 from low-pressure, low-CO_2-content gas streams at elevated temperatures, which often contain impurities like So_x and NO_x, adds complexity to the process. These challenges highlight the need for ongoing research and innovation in post-combustion CO_2 capture to improve its effectiveness and feasibility [12].

3.2 Pre combustion

The effectiveness of CO_2 pre-combustion capture technology offers a multifaceted approach to addressing carbon emissions, encompassing several noteworthy advantages and disadvantages. On the positive side, this process facilitates the production of carbon-free fuel while simultaneously capturing CO_2 at high pressure, making it an attractive option for emissions reduction. Furthermore, its versatility shines through as it can accommodate various hydrocarbon fuels, including petroleum, coal, natural gas, and biomass, ensuring adaptability across various industries. The main product of pre-combustion capture, syngas, proves valuable in combined cycle power generation and serves as a versatile feedstock for chemical synthesis applications, amplifying its utility. However, this promising technology has its challenges. Notably, it grapples with high costs and heightened risks, which can pose barriers to widespread adoption. Additionally, the process appears intricate, primarily due to the mandatory fuel conversion step before combustion into syngas. Despite these drawbacks, the effectiveness of CO_2 pre-combustion capture technology remains a compelling avenue in pursuing carbon reduction. It offers a unique blend of carbon-free fuel production and CO_2 capture capabilities, necessitating further research and development to overcome its inherent complexities and cost constraints [12].

3.3 Oxy-fuel combustion

The effectiveness of CO_2 oxy-fuel combustion presents a compelling blend of advantages and disadvantages that warrant careful consideration in the context of carbon capture and emissions reduction. On the positive side, this process yields a very high-purity CO_2 stream, simplifying purification once trace contaminants have been removed, distinguishing it from other CO_2 removal technologies. Additionally, the substantial reduction in the emission of NO_x during oxy-fuel combustion holds significant environmental benefits while simultaneously reducing the exit gas flow rate, thereby contributing to a reduction in equipment size and capital costs. Regarding design and operational flexibility, oxy-fuel combustion stands out as it has the potential for energy storage through cryogenic liquids and seamlessly integrates with steam turbine cycles without intrusiveness. However, it is essential to acknowledge the associated drawbacks. Oxy-fuel combustion imposes a high capital cost, primarily attributed to the substantial electric power required to separate oxygen from air, which can pose economic challenges for some applications. Furthermore, the process entails significant risk and safety concerns related to oxygen management and its potential impact on boiler operations. These considerations underscore the importance of a holistic evaluation when determining the suitability of CO_2 oxy-fuel combustion for emissions reduction, weighing its advantages against its cost and safety implications [12].

3.4 CO_2 Sequestration

Various methods for permanently storing carbon dioxide (CO_2) have been devised to mitigate its environmental impact. These methods encompass gaseous storage within deep geological formations, including saline formations and depleted gas fields, and solid storage, achieved by reacting CO_2 with metal oxides to produce stable carbonates. The effectiveness of CO_2 sequestration relies on evaluating three critical factors: storage capacity, containment efficiency, and injectivity, which are essential for determining the feasibility of storing CO_2 in a particular geological formation [13].

One prevalent approach is geo-sequestration, involving the injection of CO_2, typically in supercritical form, into underground geological formations. These formations can include oil fields, gas fields, saline formations, unminable coal seams, and saline-filled basalt formations. Geo-sequestration relies on physical (e.g., highly impermeable caprock) and geochemical trapping mechanisms to prevent the escape of CO_2 to the surface. Unminable coal seams, for instance, are utilized because CO_2 molecules adhere to the coal surface. The technical feasibility of this approach hinges on the coal bed's permeability. During absorption, coal releases previously absorbed methane, which can be recovered through enhanced coal bed methane recovery. While methane revenues can offset a portion of the cost, burning the resultant methane generates another stream of CO_2 that must be sequestered. Saline formations, though less explored, offer extensive potential storage volume due to their ubiquity. However, limited knowledge about these formations and the need for cost-effective storage solutions pose challenges. Unlike storage in oil fields or coal beds, there are no side products to offset storage costs. Nevertheless, trapping mechanisms like structural trapping, residual trapping, solubility trapping, and mineral trapping can immobilize CO_2 underground, thereby reducing leakage risks. Enhanced oil recovery involves injecting CO_2 into oil fields to boost production. However, the carbon neutrality of this method is disputed since CO2 is released when the oil is burned. Furthermore, long-term retention of CO_2 is essential to the effectiveness of sequestration. Properly managed sites have been estimated to have leakage risks comparable to current hydrocarbon activities. Although some leakage may occur, suitable storage sites will likely retain over 99% of the CO_2 for over a thousand years. Mineral storage is considered highly secure with minimal leakage risks [13].

In summary, the effectiveness of CO_2 sequestration methods depends on careful assessment of geological formations, trapping mechanisms, and long-term retention capabilities to ensure the permanent storage of CO_2 and minimize environmental impacts.

4 ENVIRONMENTAL IMPACTS

Carbon Capture and Storage (CCS) is a technology aimed at reducing greenhouse gas emissions, particularly carbon dioxide (CO2), from industrial processes and power generation. While CCS can help mitigate climate change by preventing CO2 from entering the atmosphere, it is essential to understand its environmental impacts and potential challenges.

4.1 Energy Consumption

Capture: The process of capturing CO2 emissions from industrial facilities and power plants can be energy-intensive. Most CCS technologies involve chemical processes or physical separation, which often require a significant amount of energy. This can reduce the overall energy efficiency of the facility, potentially leading to increased emissions of other pollutants if the energy source is not clean [14].

Transport: The compression and transportation of CO2 to storage sites through pipelines also consume energy. The length and capacity of the pipeline and the distance to the storage site influence the energy requirements [14].

Storage: While the energy requirements for injecting CO2 into storage reservoirs are relatively low compared to capture, they are still non-negligible [14].

4.2 Water Usage

Capture: Some CCS technologies, such as amine-based absorption, require substantial amounts of water for the chemical processes involved. In regions with water scarcity, this can pose a challenge [16].

Storage: Water is often used in the displacement of brines or other fluids in the geological formation to create space for the injected CO2. The amount of water needed depends on the specific geological conditions and the choice of storage site [16].

4.3 Geological Impact

Storage Site Selection: The choice of storage site is critical to minimize environmental risks. Inappropriate site selection could lead to issues like subsurface pressure changes, which may impact local geological formations and potentially trigger seismic events. [14]

4.4 Potential Leakage Risks

Storage Leakage: One of the primary environmental concerns with CCS is the risk of CO2 leakage from storage sites. If CO2 were to escape from underground reservoirs, it could migrate to the surface, potentially posing health and safety risks to nearby communities. Monitoring and verification procedures are essential to detect and address leakage promptly [14].

Transportation Leakage: Leaks can also occur during the transportation of CO2 through pipelines. These leaks can be due to pipeline corrosion, damage, or operational issues. Although CO2 is not toxic in small quantities, high concentrations in confined spaces can pose risks to human health [14].

4.5 Ecosystem and Habitat Impacts

Land Use: The construction of pipelines and infrastructure associated with CCS can disrupt local ecosystems and habitats. This may involve clearing land, impacting wildlife, and altering local landscapes [15].

4.6 Air Quality

Depending on the specific capture technology used, emissions of other pollutants, such as sulfur dioxide (SO2) and nitrogen oxides (NOx), may increase due to the energy requirements of CCS. These pollutants can have adverse effects on air quality and human health [15].

4.7 Resource Requirements

Materials: The construction and maintenance of CCS infrastructure, such as pipelines and injection wells, require materials like steel and cement, which have their own environmental impacts related to resource extraction and production [15].

4.8 Long-Term Liability

Ensuring the long-term containment and safety of CO2 storage sites requires ongoing monitoring and maintenance, which can be a financial and environmental liability if not properly managed [15].

While CCS has the potential to reduce CO2 emissions and combat climate change, it is essential to carefully consider and mitigate its environmental impacts. Proper site selection, monitoring, and regulatory frameworks are crucial to ensure the safe and sustainable deployment of CCS technologies. Additionally, ongoing research and development are necessary to improve the efficiency and reduce the environmental footprint of CCS processes.

5 ECONOMIC FEASIBILITY

CCS initiatives come with substantial costs. To illustrate, in the United States, NRG Energy and JX Nippon Oil and Gas Exploration, Inc., are dedicating approximately USD 1 billion to the Petra Nova CCS project. When this project is finalized by late 2016, it is anticipated to capture and sequester roughly 1.4 million tons of carbon annually from an existing coal-fired power plant operated by NRG in Texas, USA [20, 21]. In this section, we delve into the principles and constituents that contribute to the expenses associated with CCS.

It's important to recognize that CCS projects actually comprise two interconnected endeavors. The first aspect is "carbon capture," and the second aspect is "carbon storage." Each of these components offers various options, each with its associated costs. As previously mentioned, natural ecosystems naturally capture carbon dioxide from the atmosphere (for example, through photosynthesis) and subsequently store the captured carbon within plants, soil, rocks, and minerals. Although CCS through natural ecosystem processes and functions is a valid mitigation strategy for addressing concerns related to CO2-induced global climate change (such as tree planting), this chapter primarily focuses on the engineered CCS solutions developed by humans.

In the context of carbon capture, human-engineered methods primarily revolve around "end-of-pipe technologies." These technologies are designed to extract CO2 from industrial emissions, with a particular emphasis on power plants that use fossil fuels like coal. As of the current time frame (2016), the most advanced technology available is the chemical absorption of CO2 directly from emissions at the emission source, such as a power plant's smokestack. Once the CO2 has been successfully separated from the emissions, for example, from a coal-fired power plant, it can then be pressurized and converted into a liquid state for transportation and subsequent storage [17, 18, 22].

5.1 Components of total fixed costs and total variable costs

Therefore, one element contributing to the expenses of human-engineered carbon capture consists of the expenditures associated with the equipment, such as "scrubbers," and the chemicals used for absorption to extract CO2 from emissions [19,23]. In terms of neoclassical microeconomics theory, the costs related to the "scrubber" equipment are considered "fixed costs," while the costs for absorption chemicals are categorized as "variable costs." Fixed costs are named as such because they represent a sunk expenditure that remains constant regardless of production levels. For instance, once a coal-fired power plant owner acquires and installs scrubber equipment, they must continue to cover the equipment costs, even if they are not actively producing electricity (i.e., these costs persist as capital expenses).

Variable costs, as the name implies, fluctuate in accordance with the level of production. For instance, when a coal-fired power plant generates more (or less) electricity, it also produces a corresponding increase (or decrease) in emissions, necessitating the procurement of additional (or fewer) absorption chemicals. On the other hand, the fixed costs associated with human-engineered carbon capture can be calculated by multiplying the number of equipment units purchased by the market price per unit, which may include loan fees and interest if the equipment is financed. In contrast, the variable costs can be determined by multiplying the quantity of absorption chemicals purchased by the market price per unit.

Apart from the explicit fixed and variable costs associated with carbon capture, there are also opportunity costs related to human-engineered carbon capture. For instance, in terms of energy usage, implementing carbon capture at an electricity power plant results in an energy cost, which involves the electricity generation that needs to be foregone to facilitate carbon capture at the facility. This energy cost, often referred to as the "energy penalty," can be measured by multiplying the quantity of electricity sacrificed for the sake of carbon capture by the prevailing market price of electricity [18, 23–24].

Once carbon has been captured at a specific source, like a coal-fired electricity power plant, the next step involves its transportation and storage at a long-term storage site. As of the time this chapter is written, the most practical long-term storage sites are natural underground geologic cavities (NUGCs) in various forms. One category within this includes NUGCs that previously held crude oil and natural gas deposits but have been emptied through mining activities, such as oil and gas wells. It's worth noting that oil and gas companies are already using technology to inject captured CO2 into operational oil and gas wells to enhance resource recovery. Hence, the technology for injecting CO2, obtained from point source emissions, into NUGCs where oil and gas deposits have been depleted through mining is well-established [23,25,26].

NUGCs, where natural deposits of oil and gas have been stored by the carbon and oxygen cycle over thousands and millions of years, have demonstrated their capacity to retain newly injected CO2 within these formations for extended periods with minimal leakage back into the atmosphere. Additionally, geologists and engineers can identify new NUGCs that can store significant quantities of CO2 with minimal leakage over extended durations [23, 26].

To transport carbon captured at the source to a long-term storage site, it must undergo a process of conversion into a liquid form through pressurization. This liquid is then conveyed to the storage facility using various means such as trucks, trains, or pipelines. Assuming that natural underground geologic cavities (NUGCs) are utilized for long-term storage, the costs associated with carbon storage primarily comprise fixed and variable expenses related to the conversion of CO2 into a liquid, its transportation to the storage site, and the subsequent injection into NUGCs [23,26].

Fixed costs for carbon storage, including transportation, encompass expenditures for pressurized transport vehicles like trucks and train cars, as well as the installation of pipelines. These fixed costs also encompass the expenses associated with any equipment needed to extract captured CO2 from transport vehicles and inject it into NUGCs. Quantifying these fixed costs involves multiplying the quantity of equipment units (e.g., transport trucks or railcars) purchased by their respective market prices per unit.

Variable costs for carbon storage encompass payments for labor (for example, the workers responsible for operating and maintaining trucks, trains, pipelines, and injection equipment), the purchase of replacement parts, and the expenses related to fuel and power required to operate and maintain these vehicles and equipment. Determining these variable costs involves multiplying the number of units utilized (e.g., the count of workers) or purchased (e.g., the number of replacement parts) by the market wage rate for labor or the market price for replacement parts [22,23,26].

5.2 Measures of total marginal fixed costs and marginal variable costs

In practical terms, there are two commonly used measures in cost-benefit analysis to ensure that the costs and benefits of carbon capture and storage (CCS) can be compared on a per-unit basis for any given potential level of CO2 being captured and stored. These units are expressed over time and space as either millions of tons of carbon (MtC) or millions of tons of CO2 (MtCO2) avoided annually, denoted as MtC/year or MtCO2/year.

As previously defined in the total costs of carbon capture and storage (TCCCS), TCCCS comprises the overall fixed costs and variable costs associated with capturing carbon at the source, transporting it to the storage site, and storing it. In terms of economic efficiency, the crucial measure of the costs related to human-engineered carbon capture and storage technology is the marginal cost (MCccs). In this chapter, the marginal costs of the implemented CCS technology (MCccs) and the marginal benefits derived from using CCS technology (MBccs) are quantified in terms of US dollars per ton of carbon ($/tC) or US dollars per ton of carbon dioxide ($/tCO2), where one ton of carbon is equivalent to 3.67 tons of carbon dioxide [19].

According to recent studies, the estimated marginal cost of carbon capture and storage (MCccs) per unit falls within the range of US \$225/tC to \$315/tC (equivalent to US \$61/tCO2 to \$86/tCO2). However, it's important to note that significant reductions in MCccs are expected in the near future due to ongoing technological advancements in CCS [22]. To provide a comprehensive overview of these findings, the estimates of marginal cost savings can be broken down into three cost components:

- Marginal costs associated with capturing carbon at the source vary between US \$200/tC and \$250/tC [22].
- Marginal costs for transporting captured carbon to the storage site range from US \$5/tC to \$10/tC per 100 kilometres [22].
- Marginal costs associated with storing carbon at the storage site, which fall within the range of US \$20/tC to \$55/tC [27].

6 LONG-TERM STORAGE TECHNOLOGIES

6.1 Geological storage

The CCS method is widely regarded as the most appealing option for capturing carbon dioxide (a greenhouse gas) emanating from stationary (like power plants) and mobile sources (such as automobiles), then depositing these emissions into geological formations. This process contributes to sustainable environmental progress and long-lasting carbon dioxide storage [28]. Similar geological formations can store CO2 generated by industrial activities for centuries in a variety of locations throughout the globe. Despite the fact that geologic storage of gases occur naturally and has been utilized safely by industry for many years, it is still difficult to explain this process to the general public. Fortunately, these formations may be found in many places around the world; the majority are in sizable geological structures known as sedimentary basins. Sedimentary basins account for the majority of oil and gas production, and reservoirs for storing CO2 can be found in the same kinds of geologic formations that trap oil, gas, and naturally occurring CO2 [29].

An essential element in the storage of carbon dioxide within deep geological formations, and in guaranteeing its containment, involves a setup consisting of layered, deeply buried rock formations with permeable qualities that function as the reservoir for CO2 storage. These are covered by two impermeable caprocks, which play a vital role in securing the injected CO2 in its position. A comprehensive assessment of these formations and their capacity to receive and maintain the injected CO2 is imperative and should be a fundamental part of the site evaluation process before any CO2 injection is considered [30].

6.1.1 CO_2 injection into deep geological storage formation

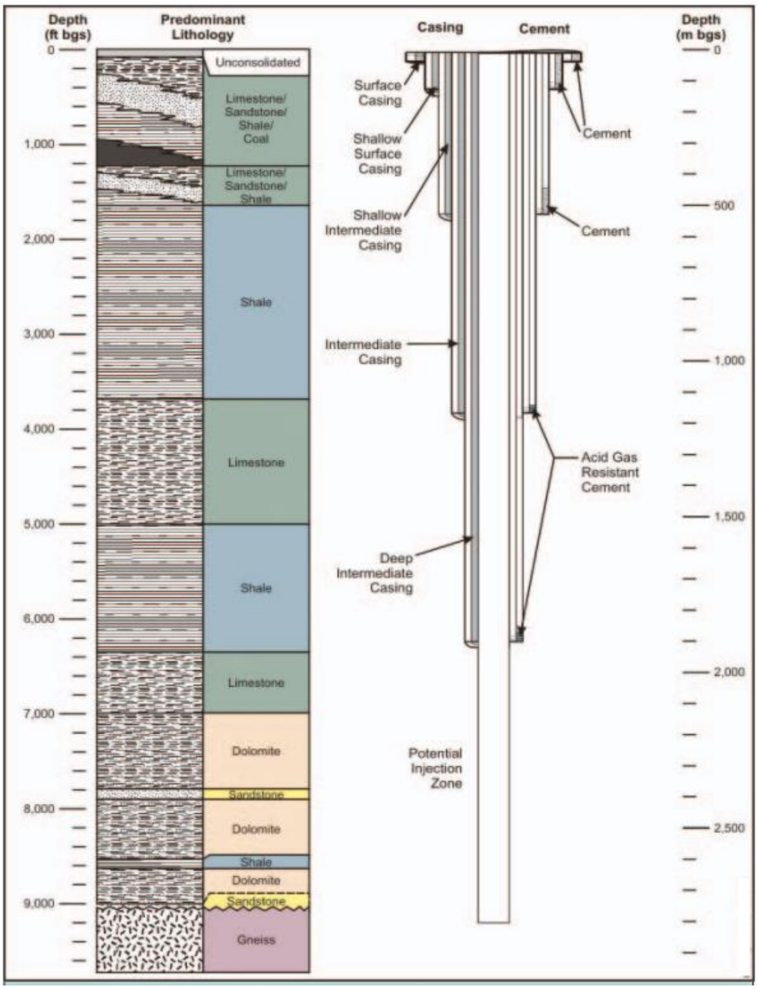

Fig. 4. CO2 injection well [30]

Fig. 4. illustrates CO2 injection well. As can be seen from the schematic below, CO2 injection constitutes a well-engineered system. A CO2 injection well comprises multiple casings designed to safeguard the exclusive entry of CO2 into the designated injection zones, preventing any interference with shallower sources of drinking water. These drinking water sources are situated much closer to the surface compared to the potential CO2 storage formations. The CO2 injection well traverse numerous geological layers, spanning thousands of feet, before reaching the desired CO2 storage formations. These formations consist of rocks that are both ancient and deeply buried [30].

6.2 Ocean storage

The possibility of directly introducing CO2 into the deep ocean, where the majority of it will dissolve as bicarbonate, represents one approach to CO2 storage. This method can be viewed as expediting the natural absorption of CO2 by the ocean, a process that would naturally take place over an extended period, spanning centuries. Regrettably, due to ocean currents and localized oversaturation, a significant portion of the injected CO2 will escape into the atmosphere within a few hundred years. Furthermore, the concept of direct ocean storage is presently met with resistance due to concerns regarding the impact of CO2 on marine ecosystems [31].

Conventional storage methods confine captured CO2 as either a liquid or gas in deep underground geological formations, typically within designated structures like abandoned hydrocarbon wells. These methods necessitate the use of an impermeable seal to close the injection opening and prevent any potential release. In contrast, ocean-based CO2 storage involves the deliberate injection of gas into the deep ocean, where it can either naturally disperse or be intentionally trapped in a specific location, contingent on factors like depth and pressure [32].

The feasibility of deep-sea storage is limited by the amount of available CO2. Although emissions from specific sources are estimated to be around 15 billion tons annually, the current capacity for capturing and storing CO2 is less than 30 million tons. Another significant challenge is the transportation of CO2, given the very restricted pipeline infrastructure in place [33].

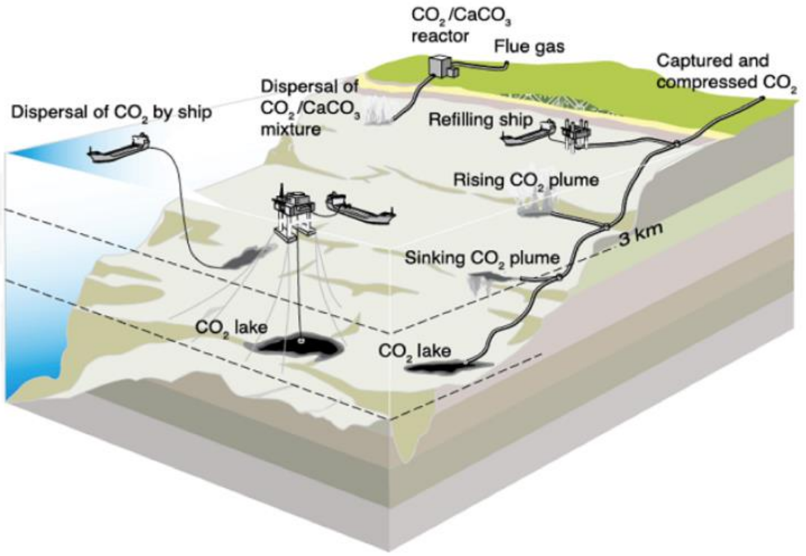

Fig. 5. -Different methods of injection for ocean storage of CO2 [32]

There are three primary approaches for directly introducing carbon dioxide into the ocean for storage. The first involves a pipeline that stretches from the shoreline to the ocean's depths. This pipeline would receive a continuous supply of carbon dioxide from a capture or interim storage facility along the coast and transport it offshore for long-term storage. In the second method, known as dispersal by ship, CO2 stored onboard the vessel would be discharged at significant depths using an extended hose or pipe that trails behind the vessel, facilitating the rapid diffusion of CO2 into seawater. The third method entails employing a stationary vessel or platform to inject CO2 into a fixed location either at or close to the ocean floor [32]. Fig. 5. Shows different methods of injection for ocean storage of CO2.

Currently, all marine CCS projects, whether in operation or in the planning stages, store their carbon dioxide in saline aquifers or depleted gas fields, both of which are considered highly resistant to leakage. However, the injection of liquid CO2 into the water column is a different scenario, as it will disperse into the surrounding seawater and create localized areas of ocean acidification at levels that could potentially harm marine ecosystems. Over the course of centuries to millennia, this CO2 might resurface and re-enter the atmosphere. On the other hand, carbon storage in solid forms may lead to the destruction of local habitats [33].

7 POLICY AND REGULATORY FRAMEWORK

Carbon capture and storage (CCS) is poised as a pivotal technology in the global pursuit of reducing carbon dioxide emissions. However, its adoption hinges significantly on the regulatory environment and government incentives. This review article delves into the world of CCS policies, international agreements, and sustainable steps taken by nations to foster their development.

As the urgency of addressing climate change intensifies, the role of CCS technology becomes increasingly prominent. This article sheds light on the vital interplay between government policies, international agreements, and CCS adoption.

7.1 International Agreements: A Framework for CCS Governance

London 1972 Convention and United Nations 1982 Convention on the Law of the Sea: These United Nations conventions play a pivotal role in regulating activities related to the seas, including the continental shelf. They provide the essential legal framework for addressing the legality of CO2 sequestration near the continental shelf. An amendment, allowing industrial CO2 capture and disposal at sea, aligns with international and national laws. China's 1985 endorsement underscores the conventions' significance in governing CO2 storage activities [34].

United Nations Framework Convention on Climate Change (UNFCCC) 1992: Established in 1992, the UNFCCC champions international cooperation in addressing climate change. It encourages nations to explore sustainable strategies for managing and enhancing carbon sinks and stocks. China's 1993 ratification commits to research, promoting renewable energy sources, and innovating technologies, including CO2 sequestration [34].

Kyoto Protocol and Marrakech Agreement (1997): These agreements emphasize collaboration among signatory nations, urging the development, promotion, and transfer of technologies for GHG emission capture and storage. The involvement of the IPCC in compiling technical documents further propels CCS cooperation. China's 2002 approval signifies its dedication to these cooperative endeavors [34].

7.2 Sustainable Steps Toward CCS Adoption

USA: With a commitment of $2.4 billion from the economic stimulus plan, the US government accelerates CCS technology development. The American Clean Energy and Security Act earmarks 26% of emission reduction subsidies for supporting CCS development and related projects.

Australia: Australia initiates its "CCS Flagship Project" with a $2 billion allocation for CCS research. The formation of the Global CCS Institute underscores the nation's dedication to CCS development on a global scale.

EU: The EU leads in CCS technology research and development, advocating for institutionalization and standardization of relevant legislation. The European Commission, European Parliament, European Council, and European Investment Bank prioritize CCS as a high-priority development technology [34].

7.3 Influence of Government Incentives and Mandates on CCS Adoption

- *Financial Support:* Government funding for research and development significantly expedites CCS technology progress, exemplified by the substantial investments in the USA and Australia.
- *Emission Reduction Subsidies:* Mandating a portion of emission reduction subsidies for supporting CCS development, as seen in the American Clean Energy and Security Act, encourages enterprises to invest in CCS technology.
- *Priority Development Technologies:* The EU's recognition of CCS as a high-priority technology garners attention and resources, amplifying its advancement.
- *Legislative Framework:* The EU's issuance of directives to establish a legal framework for CCS development underscores its commitment to supporting and regulating CCS, facilitating technology adoption [34].

As nations grapple with the pressing issue of climate change, CCS emerges as a beacon of hope. Through international agreements, sustainable initiatives, and government incentives, the world takes decisive steps toward realizing the potential of CCS in the fight against carbon emissions. The interplay of policy and technology promises a brighter, more sustainable future for generations to come. The study unequivocally concludes that the significance of state regulation cannot be overstated in achieving positive CCS project outcomes. Therefore, government mandates and incentives emerge as indispensable catalysts for the triumphant realization of CCS initiatives [35].

8 CHALLENGES

8.1 Challenges

- **Cost:** Integrating Carbon Capture, Utilization, and Storage (CCUS) imposes an additional financial burden on various industries, without presenting substantial revenue-generating prospects at present. While federal tax credits serve to partially mitigate the significant expenses associated with CCUS for certain entities, they are not universally applicable [36]. An overarching obstacle hindering the efficacy of carbon capture technologies in addressing climate change primarily revolves around economic factors. The expenditure involved in capturing one metric ton of CO2 typically ranges from $40 to $80, with even higher costs of approximately $200 to $600 for direct air capture [37].

- **Infrastructure development:** Expanding the use of CCUS necessitates the establishment of infrastructure for all its components, encompassing transportation and storage. The timeline for development, negotiations for land access, and the proximity of facilities pose significant hurdles in this expansion [36]. Furthermore, the process of capturing emissions is exceptionally energy-intensive. In instances where a coal plant is equipped with CCS technology, it may require roughly 25% more fuel to produce the same amount of power as a non-equipped plant. To illustrate this energy demand, take the example of the Petra Nova carbon capture facility in Texas, which consumed a substantial amount of energy solely to operate the scrubber. This demand was so significant that NRG had to construct an entirely separate natural gas power plant to meet it [37].

  Another substantial challenge in the adoption of carbon capture technologies is determining the fate of the captured CO2. Typically, there are two options: underground storage or selling it to buyers to generate revenue. Up to now, the most prevalent use has been underground storage, primarily for enhanced oil recovery. This practice involves injecting CO2 into oil wells to enhance oil production. However, it remains controversial because it essentially employs carbon dioxide to access more oil, which, when burned, releases additional CO2 into the atmosphere [37].

- **Community engagement:** The successful execution of CCUS projects is contingent upon receiving approval from and engaging effectively with local communities. Historically, instances of ineffective community engagement and local resistance have played a part in the abandonment or relocation of certain CCUS initiatives, while others have been positively embraced [36].

8.2 Improvement efforts

New technologies are in development to reduce expenses related to the capture of carbon and its high energy consumption. Researchers at EPFL have successfully crafted a novel graphene filter capable of isolating CO2 from other gases. This breakthrough has the potential to decrease the expenses associated with carbon capture to just $30 per ton of CO2, while also enhancing the speed and efficiency of the process [37].

Enterprises like Noya Labs are actively devising creative solutions to address the scalability issue. This startup aims to lower costs by repurposing existing infrastructure and converting cooling towers into devices that can absorb CO2. Noya Labs asserts that their approach can bring the cost of capturing a ton of CO2 down to $100, a significant improvement compared to the market price range of $125 to $5000 per ton. According to the founders, there is growing competition among buyers seeking to secure CO2 at Noya Labs' competitive price point [37].

Despite the challenges involved, expanding Carbon Capture, Utilization, and Storage (CCUS) efforts may be a matter of global necessity. Innovative companies worldwide are actively working to address the hurdles associated with CCUS, and they are now closer than ever to advancing capture technology and reducing the expenses associated with the storage and utilization of CO2 [37].

9 CASE STUDIES

9.1 Successful Projects

9.1.1 Quest CCS Project

The Quest CCS Project, initiated in November 2015, represents a critical step in addressing climate change by capturing over one million metric tons of CO2 emissions annually from Shell's Scotford Upgrader in Alberta, Canada. With the goal of reducing emissions by one-third from the upgrader, the project includes three test wells for CO2 capture and transport via pipelines to the Radway field for storage in the Cambrian Basal Sands [38].

Shell's commitment to sustainability began with the Scotford upgrader expansion in May 2011, significantly increasing capacity to 255,000 barrels per day. Environmental concerns were addressed in a 2012 report concluding that the Quest CCS Project, with mitigation measures, wouldn't result in significant adverse environmental effects. A pivotal moment was reached in August 2014 when Shell Canada completed construction [38].

This project's significance extends beyond Shell, as it received funding from the Alberta and Canadian federal governments, showcasing collaborative efforts to mitigate greenhouse gas emissions. In conclusion, Shell's Quest CCS Project is a beacon of hope in the fight against climate change, exemplifying carbon capture and storage technology's potential and the importance of industry-government collaboration for a sustainable future. Meeting CCS emission reduction targets necessitates prompt action, supported by incentive policies and carbon pricing, as seen in successful projects worldwide [38].

9.1.2 Gorgon CCS Project

The Gorgon Carbon Sequestration Project in Australia represents a historic step toward environmental responsibility as the nation's first carbon dioxide (CO2) sequestration initiative. Supported by the Australian Government, this project aims to become the world's largest sequestration effort, demonstrating Australia's commitment to greenhouse gas mitigation.[39]

The Australian Government's strong support was evident when it assumed liability for the project in 2009, with construction commencing in 2009 and all necessary permits obtained by 2010. Although there were minor delays, the project's resolve remained unshaken [39].

The Gorgon Carbon Sequestration Project plans to capture and store a substantial 120 million tons of CO2 over its lifetime, equivalent to 40 percent of its emissions. Located in the Greater Gorgon Fields, the project leverages the substantial CO2 content (14 percent) in the gas reservoirs. Gas is transported through an onshore pipeline to Barrow Island, where meticulous CO2 capture and storage are planned. The target reservoir is the Dupuy Formation, protected by the Barrow group marine shale formation [39].

9.1.3 Petra Nova CCS Project

The Petra Nova CCS project is a groundbreaking initiative in the field of carbon capture and utilization. Supported by the U.S. Department of Energy (DOE), it began with NRG Energy Inc. and later transitioned to Petra Nova Parish Holdings, LLC, a joint venture between NRG Energy and JX Nippon Oil & Gas Exploration. The project received substantial financial backing, totaling $190 million in cost share, including funds from the Clean Coal Power Initiative (CCPI) Round 3 and the Recovery Act [40].

Its primary objective is to integrate a commercial-scale post-combustion carbon capture technology into the existing W.A. Parish Generating Station, aiming to capture an impressive 90 percent of carbon dioxide (CO2) emissions from a 240 MW flue gas stream, totaling approximately 1.4 million metric tons of CO2 annually [40].

The project utilizes a proven carbon capture process developed by Mitsubishi Heavy Industries, Ltd. (MHI) and the Kansai Electric Power Co., involving a high-performance solvent for CO2 absorption and desorption. Captured CO2 is compressed and transported via an 80-mile pipeline to an operational oil field, where it is used for enhanced oil recovery (EOR) before being sequestered [40].

Located in Thompson, Texas, the project involves several key partners, including Mitsubishi Heavy Industries America, Sargent & Lundy, The Industrial Company, and the University of

Texas, Bureau of Economic Geology. Operational since January 2017, it showcases the potential of carbon capture and utilization in advancing environmental responsibility and sustainability [40].

9.2 Unsuccessful

9.2.1 Kemper CCS Project

The Kemper County Power Plant in Mississippi, initially estimated at $2.2 billion, has faced a tumultuous journey, with costs surging to $6.66 billion. Despite receiving a $270 million grant from the Department of Energy and $133 million in tax credits, the project encountered challenges with missed deadlines, resulting in financial penalties and potential loss of tax benefits. Southern Company withdrew its federal loan guarantee application in 2013, opting for alternative financing, further complicating the project's financial landscape [41].

Mississippi Power had to borrow from Southern Co. to cover various financial obligations, including refunding illegal rate increases and repaying a deposit. Despite these setbacks, the Kemper County Power Plant symbolizes the energy industry's commitment to cleaner coal-based energy production and the pursuit of innovative solutions for sustainable power generation. It serves as a lesson in navigating the complexities of ambitious clean energy projects within the evolving energy landscape [41].

9.2.2 Hydrogen Energy California CCS Project

The Hydrogen Energy California project, initially hailed as an innovative and environmentally responsible energy solution, faced formidable challenges leading to its abandonment. Obtaining permits for its unique combination of integrated gasification combined cycle (IGCC) and fertilizer plants with carbon capture and storage (CCS) proved complex and time-consuming. Planning a railroad extension for resource transportation added logistical complexity and cost considerations [42].

Securing additional financing for its ambitious hydrogen generation from coal and pet coke gasification was a persistent challenge, despite significant funding from sources like the U.S. Department of Energy (DOE). The project's commitment to capturing and storing 90 percent of CO2 emissions for enhanced oil recovery (EOR) and urea-based nitrogen fertilizers posed environmental concerns regarding CO2 release [42].

Despite substantial financial support, including USD 408 million in DOE funding and USD 437 million in tax credits, the project encountered delays, issues with CO2 sales agreements, and stagnation. In March 2016, it took a significant step by withdrawing its Application for Certification, citing difficulties in finding suitable CO2 offtake solutions. Speculation arose about a potential future revival, possibly as a non-EOR storage option, contingent upon a comprehensive reevaluation [42].

In essence, the Hydrogen Energy California project illustrates the intricate challenges inherent in pioneering clean energy initiatives. While initially promising, its journey illuminates the multifaceted obstacles that can hinder ambitious environmental projects. Nevertheless, the knowledge acquired from this venture continues to influence the development of sustainable and responsible energy solutions [42].

10 FUTURE PROSPECTS

10.1 Emerging Technologies

10.1.1 Bioenergy with Carbon Capture and Storage (BECCS)

Bioenergy is produced from biological sources like forest residue, energy crops, and biodegradable matter. This energy is released by burning these materials. CCS technology captures CO2 emissions to prevent them from re-entering the atmosphere. BECCS combines bioenergy production with carbon capture and storage. Currently, there are exploratory projects worldwide, but none have been commercialized. According to the IEA, BECCS could sequester 10Gt of CO2 by 2050, potentially achieving net negative emissions. However, it is costly and would raise electricity costs. It also has both positive (reduced emissions) and negative (land use changes) environmental impacts. Social effects include job creation and market effects, like potential increases in food prices. Challenges to BECCS adoption include biomass sustainability, affordability, and public perception. Recommendations for successful implementation include regulations, carbon taxes, co-firing, and managed forestry strategies [43].

10.1.2 Use Amine-based solvents to capture CO2.

Traditional amine-based solvents have long been the go-to method for removing CO2 and H2S in chemical absorption. This process involves using amines to absorb CO2 and form a soluble carbonate salt. It's widely used in industries like power plants, cement production, and steel manufacturing to reduce carbon emissions. Primary alkanolamines like MEA and DGA are known for their high reactivity, preferred kinetics, and medium to low absorption potential. MEA, a first-generation amine, stands out for its high reactivity and affordability. Secondary alkanol amines like DEA and DIPA offer intermediate properties and are considered alternatives to MEA. Tertiary amines like TEA and MDEA have low absorption potential, reactivity, and high stability. Sterically hindered amines, including amino alcohols, can enhance CO2 absorption rates. Non-amine-based solvents, like Na2CO3 and ionic liquids, provide alternatives. Newer solvents like amino silicones, organic blends, and others show promise for improving CO2 capture [44].

10.2 Research Areas

CCS technology, while promising, faces notable challenges. High implementation costs and the need for suitable storage sites pose significant hurdles, along with concerns about safety and environmental impact. Efforts to overcome these include substantial investment in research and development.

Innovative financing approaches like carbon pricing and tax incentives can enhance the economic viability of CCS. Collaboration between policymakers and the private sector is crucial to establish favorable regulatory frameworks. Currently, three main types of CCS technologies are under research and implementation: post-combustion capture, pre-combustion capture, and oxy-fuel combustion, each tailored to specific emissions reduction goals.

Several large-scale CCS projects are already underway globally. Notable examples include Norway's Sleipner project, operational since 1996, which captures CO2 from natural gas production and stores it underground. In the US, the Petra Nova project utilizes captured CO2 from a coal-fired plant to enhance oil production in an advanced recovery process. These initiatives demonstrate the viability of CCS as a means to significantly reduce emissions [45].

10.3 Role in Achieving Global Climate Goals

Geological storage is considered the safest method for reducing greenhouse gases (GHG) in the atmosphere. While the ocean offers a vast area for storage, concerns about ocean acidification due to increased CO2 levels have been raised. Despite the energy cost of CCS technology on incinerator operations, life cycle assessment (LCA) models demonstrate that CCS significantly reduces climate change impacts from waste incineration. Overall, CCS has a positive effect on lowering global warming potential (GWP), but the growing demand for infrastructure fuel leads to environmental trade-offs, including increased GHG emissions and impacts like acidification, eutrophication, and toxicity [46].

10.3.1 Meeting Net Zero Targets

- The initial focus of CCUS (carbon capture, utilization, and storage technologies) is on retrofitting existing fossil fuel-based power and industrial plants as well as lower-cost CO2 capture opportunities such as hydrogen production. Over time, the focus shifts to bioenergy with CCS (BECCS) and direct air capture (DAC) for carbon removal and as a source of climate-neutral CO2 for use in various applications, particularly synthetic fuels.

- In the IEA Sustainable Development Scenario, in which global CO2 emissions from the energy sector fall to zero on a net basis by 2070, CCUS accounts for nearly 15% of the cumulative reduction in emissions compared with the Stated Policies Scenario. The contribution of CCUS grows over time as technology improves, costs fall and cheaper abatement options in some sectors are exhausted. In 2070, 10.4 Gt of CO2 is captured from across the energy sector [47].

10.3.2 Enabling negative emissions

Successful deployment of BECCS at scale would require the coordinated development of each component of the supply chain. Governments and the private sector have an important role in this regard. Opportunities that maximize the removal and mitigation potential of BECCS while limiting its economic, environmental and social costs can be identified through the mapping and matching of sustainable biomass supply, existing bioenergy facilities, industrial clusters, and potential CO, storage sites. Focusing on biomass facilities within industrial clusters can help leverage economies of scale and aggregation.

Companies will need to limit the impacts of producing, transporting and pretreating sustainable biomass. Key considerations when retrofitting larger coal plants to accept biomass, or building new biomass facilities, include:

- life cycle CO, emissions, and energy use of biomass supply and BECCS plant operation
- land use change
- effects on the natural carbon cycle and biodiversity

- fuel-food and fiber production balance [48].

10.3.3 Supporting a just transition

CCS are in all cases associated with a significant transformation of the energy system in response to climate change. Hence, it shows a significant decrease in total global fossil fuels consumption, as well as a significant increase in efficiency across electricity production and industrial processes.

- Accept a broad array of fiscal instruments to encourage CCS.
- Address capturing and storing carbon dioxide from all industrial sectors, including cement, steel, chemicals, refining and power production.
- Ensure that Governments work together to sponsor and support multiple demonstration projects at scale.
- Allow carbon dioxide injected into reservoirs for enhanced hydrocarbon recovery to be treated and calculated as storage if stored permanently [49].

11 CONCLUSIONS

In conclusion, Carbon Capture and Storage (CCS) technologies hold immense promise in the battle against climate change. They offer a multifaceted approach to curbing greenhouse gas emissions from diverse sources, including power plants, industrial processes, and natural gas production. The effectiveness of CCS is evident, but it comes with environmental concerns, chiefly related to energy and water use and potential leakage risks. The economic feasibility of CCS is challenging but may improve with innovation and policy support. Sustainability is a key concern, and the long-term storage of captured CO2 demands rigorous monitoring and regulatory oversight. Existing policies and regulations, along with government incentives, play pivotal roles in shaping the adoption of CCS technologies. However, significant challenges like public acceptance, infrastructure development, and technological advancements remain to be addressed. Real-world case studies illustrate the potential and pitfalls of CCS projects, emphasizing the need for careful planning and execution. Looking ahead, emerging technologies and continued research are poised to enhance CCS efficiency and affordability, positioning it as a crucial player in achieving global climate goals.

In this context, it is evident that CCS is not a silver bullet but a vital component of a diversified approach to climate change mitigation. It underscores the urgency of adopting and refining CCS technologies to reduce greenhouse gas emissions and safeguard the planet for future generations. As we strive for a sustainable and carbon-neutral future, CCS stands as a critical ally in the fight against climate change.

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