Journal of Environmental Engineering and Energy

www.jeee.reapress.com

J. Environ. Eng. Energy. Vol. 1, No. 1 (2024) 1–15.

Paper Type: Original Article

Conventional Trends on Carbon Capture and Storage in the 21st Century: A Framework for Environmental Sustainability

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Citation:

Received: 17 June 2024 *Revised: 29 July 2024* *Accepted: 10 August 2024*	Essienubong Ikpe, A., Ime Ekanem, I., & Rechard Ekanem, K. (2024). Conventional trends on carbon capture and storage in the 21st century: a framework for environmental sustainability. Journal of Environmental Engineering and Energy, *1*(1), 1-15.

Abstract

This study aimed to explore the conventional trends in Carbon Capture and Storage (CCS) and evaluate its potential as a framework for environmental sustainability. The methodology involved a comprehensive review of research studies, reports, and case studies related to CCS implementation in various industries and regions. The review included an assessment of the current status of CCS projects worldwide and their effectiveness in reducing carbon emissions. The study also examined the regulatory frameworks and policy incentives that support deploying CCS technologies for environmental sustainability. In addition, the study evaluated different types of CCS technologies and their effectiveness in capturing and storing CO2 emissions. The evaluation also delved into the environmental risks and benefits associated with CCS, including potential leakage of stored CO_2 and using energy-intensive processes for capture and storage. The study revealed that several CCS projects have been successfully implemented in power plants, cement factories, and other industrial facilities, demonstrating the feasibility of capturing and storing CO_2 emissions. However, the high costs associated with CCS deployment remain a significant barrier to widespread adoption. The lack of public awareness and acceptance of CCS technologies posed challenges to their implementation on a larger scale. The long-term storage of CO_2 and the environmental impacts of CCS operations were some of the concerns noted about the sustainability of this technology. Despite these challenges, CCS has the potential to play a crucial role in achieving environmental sustainability by reducing carbon emissions and transitioning to a low-carbon economy.

Keywords: Carbon capture, Carbon storage, Emission reduction, Environmental sustainability.

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1 | Introduction

The scientific community has made it quite obvious that we must employ all available means to mitigate the worst effects of climate change, the most pressing problem confronting humanity today. Two of the world's most prominent climate and energy organizations, the International Energy Agency (IEA) and the United Nations' Intergovernmental Panel on Climate Change (IPCC) have identified Carbon Capture and Storage (CCS) as a critical component in achieving zero emissions by 2050. Studies have indicated that CCS could significantly reduce global CO_2 emissions by 2050, helping to limit global warming to below 2 ^{o}C. This is crucial for achieving the goals set out in the Paris Agreement and transitioning to a low-carbon economy [1, 2]. Moreover, CCS technology can play a role in enabling the use of carbon-neutral fuels such as hydrogen, which can help reduce emissions from sectors such as transportation and heating. By capturing CO_2 emissions from hydrogen production and storing it underground, CCS can ensure that the use of hydrogen remains environmentally sustainable. In addition, CCS can help promote sustainable development by creating new economic opportunities and jobs in the clean energy sector. Deploying CCS infrastructure, such as pipelines and storage sites, can stimulate investment and innovation in the green economy, creating new jobs and economic growth. Time is of the essence in the race to minimize global emissions, and CCS is rapidly becoming an essential component of any practical strategy to combat climate change [1]. Both natural processes and human actions contribute significantly to the atmospheric concentration of CO_2. Most animals produce CO_2 through their exhalation, making them a natural supply of this gas.

The combustion of fossil fuels, such as coal, oil, or natural gas, is the primary human activity that releases CO_2 into the atmosphere. Industries that rely on a great deal of energy to operate, such as electricity generation and manufacturing, make decarbonization a formidable challenge. Energy accounts for more than 70% of the world's emissions. CCS is one of the few proven methods to decarbonize these industries cost-effectively and sustainably. Carbon capture, usage, and storage (CCUS) is a method that prevents CO_2 emissions from sources such as coal-fired power plants from reaching the environment. It recycles or preserves the captured CO_2. Another name for this process is carbon capture, utilization, and sequestration. Geologic formations, including oil and gas reservoirs, deep saline reservoirs, and unmineable coal seams, have stored carbon dioxide for countless years [3]. We anticipate that it will significantly contribute to achieving global climate objectives. To keep global warming below 1.5°C, leading organizations such as the International Renewable Energy Agency (IRENA), North East CCUS (NECCUS), Bloomberg New Energy Finance (BNEF), and the International Energy Agency (IEA) have collectively developed long-term energy projections that depend on the rapid proliferation of CCUS. CCS techniques extract CO_2 from various industrial processes, treat it, and transport it to a site for extended storage. Essentially, it is a method that reduces CO_2 emissions into the atmosphere to combat climate change. The objective is to permanently remove CO_2 from the atmosphere by storing it underground. Until we can implement low-carbon alternatives, we can consider CCS as an approach that permits the continuous use of fossil fuels in power production and manufacturing. According to the IPCC's fifth assessment report, it would cost about 138% more worldwide to limit the increase in global temperatures to a maximum of two degrees Celsius without CCS. Consequently, if we want to reach the 1.5°C and 2°C climate goals, which involve negative CO_2 emissions, CCS can also be essential.

Capturing and storing massive quantities of CO_2 is necessary for CCS to considerably lower carbon emissions [4]. Most of the time, major point sources like chemical or bioenergy plants collect CO_2 and sequester it in an appropriate geological formation. Lessening the production of greenhouse gases will help slow global warming. One strategy to reduce power sector emissions and achieve the targets outlined in the Paris Agreement is to retrofit current nuclear plants with CCS technology. CO_2 can be collected directly from the gaseous by-products of an industrial operation, such as a cement kiln. Its applications include assisting decarbonization efforts in industrial processes that rely on hydrocarbons for energy generation, such as those involved in manufacturing steel, cement, or chemicals. These considerations make it harder to replace oil and gas with low-carbon alternatives. In 2022, most CCS initiatives involved refining natural gas, contributing significantly to the collected CO_2 emissions. Although 90% capture efficiency is the standard for CCS projects, most existing systems are falling short of this mark [5]. Although CCS is currently pricey, it could become more practical when carbon prices are high. Another possibility is integrating CCS with a utilization process that turns the collected CO_2 into valuable compounds to counteract the hefty price tag of capture processes.

Several politicians and environmentalists view CCS sceptically as an ineffective remedy to the global catastrophe. The petroleum and coal industries are responsible for both the development of the process and the promotion of laws centred on CCS. Some people think that CCS is nothing more than fraudulent claims for the fossil fuel industry's negative impact on society and ecology. Communities that have suffered because of industrialization tend to be less in favour of CCS when it comes to public acceptance. Additionally, communities may oppose CCS development if they feel uninformed or left out of project decision-making processes.

2 | Properties of Carbon Dioxide

Carbon dioxide is a chemical molecule represented by the chemical formula CO_2. The substance consists of molecules, each containing a single atom covalently double bonded to two oxygen atoms and properties presented in *Table 1*. At ambient temperature, atmospheric CO_2 exists in the gaseous state and serves as the primary carbon source for life on Earth in the carbon cycle. CO_2 is invisible to visible light but absorbs infrared radiation in the air, making it a greenhouse gas. CO_2 is soluble in water and is present in groundwater, lakes, ice caps, and seas. Ocean acidification is caused by the dissolution of carbon dioxide in water, resulting in carbonate and primarily bicarbonate, when atmospheric levels of CO_2 rise [6].

Table 1. Properties of carbon dioxide [7].

Properties	Values
Chemical formula	CO_2
Appearance	Colourless gas
Odour	Low concentrations: none High concentrations: sharp, acidic
Flammability	Non-flammable gas
Molecular mass	44.009 $g \cdot mol^{-1}$
Specific gravity	1.53 at 21 ^{o}C
Melting point and boiling point	-55.6°C and -78.5°C
Density	1.977g/ml
Soluble in water	Solubility decreases as temperature increases
Critical density	468 kg/m^3
Concentration in air	$370{,}3 * 10^7$ ppm
Stability	High
Liquid	Pressure < 415.8 kPa
Solid	Temperature < -78 ^{o}C
Henry constant for solubility	298.15 mol/ kg * bar
Water solubility	0.9 vol/vol at 20 ^{o}C
Magnetic susceptibility	$-20.5 \cdot 10^{-6}$ cm^3/mol
Thermal conductivity	0.01662 $W \cdot m^{-1} \cdot K^{-1}$
Refractive index (nD)	1.00045
Heat capacity(C)	37.135 J/(K·mol)

3 | Developments in the CCS Process

CCS has been a topic of significant interest and research in recent years as a potential solution to mitigate the impacts of climate change. This technology has the potential to significantly reduce greenhouse gas emissions and help countries meet their climate targets. CCS technology has been hailed as a key solution to reducing greenhouse gas emissions and combating climate change. Over the years, significant developments in CCS technology have occurred, with key milestones marking important progress in the field.

I. CCS is a technology proposed to mitigate the effects of climate change by capturing carbon dioxide emissions from industrial processes and storing them underground. The concept of CCS dates back to the 1970s when researchers first began exploring ways to reduce greenhouse gas emissions. However, it was not until the early 2000s that CCS gained widespread attention as a potential tool for combating climate change [8].

II. One of the critical developments in CCS technology was the demonstration of the first commercial-scale CCS project. This project, known as the Sleipner project, was launched in 1996 by Norwegian oil company Statoil. The project involved capturing CO_2 emissions from a natural gas processing plant and injecting them into a deep saline aquifer beneath the North Sea. The success of the Sleipner project demonstrated the feasibility of CCS technology on a large scale and paved the way for further developments in the field [9].

III. One of the earliest recorded developments in CCS technology being implemented on a large scale was in 2000 when the Sleipner gas field in Norway began injecting captured carbon dioxide into a saline aquifer deep underground. This project demonstrated CCS's feasibility in reducing carbon emissions from industrial sources [10].

IV. In the years following the Sleipner project, several other CCS projects were initiated worldwide, including the Weyburn-Midale project in Canada in 2000 and the In Salah project in Algeria in 2004. These projects further demonstrated the potential of CCS technology to reduce carbon emissions and combat climate change [11].

V. Another key milestone in developing CCS technology was establishing the first commercial-scale CCS project in 2014. The Boundary Dam CCS project in Saskatchewan, Canada, demonstrated the feasibility of capturing CO_2 emissions from a coal-fired power plant and storing it underground. This project paved the way for other CCS projects worldwide and showed that CCS technology could be deployed at a large scale [12].

VI. Another critical development in CCS technology was the development of new capture technologies that are more efficient and cost-effective. Traditional CCS technologies, such as amine scrubbing, are energy-intensive and expensive, while developments, such as pre-combustion capture and oxyfuel combustion, have significantly improved efficiency and cost-effectiveness. However, new technologies, such as solvent-based capture and membrane separation, have been developed to be more efficient and cost-effective. These developments have made CCS more economically viable and have increased interest in deploying CCS technology in various industries [13].

VII. The development of CCS projects in different sectors, such as power generation, industrial processes, and transportation, has also been a critical milestone in the development of CCS technology. These projects have demonstrated the versatility of CCS technology and its potential to reduce emissions across a wide range of industries. For example, the Boundary Dam CCS project in Canada, which captures CO_2 emissions from a coal-fired power plant, has shown that CCS can be successfully applied to the power generation sector [14].

The development of commercial-scale projects, new capture technologies, and projects in different sectors have all contributed to the development of CCS technology. Governments, industry, and researchers must continue to work together to overcome challenges and accelerate the widespread deployment of CCS technology to help mitigate the impacts of climate change.

4 | Types of CCS Technology

Various carbon capture techniques are currently being developed and implemented, each with advantages and limitations. These include the following:

I. One of the most commonly used carbon capture techniques is post-combustion capture, which involves capturing CO2 from the flue gas of power plants and industrial facilities after combustion. This method typically uses chemical solvents or adsorbents to capture CO_2, which can then be transported and stored underground in geological formations. While post-combustion capture is relatively mature and can be retrofitted to existing facilities, it is energy-intensive and costly to implement on a large scale [15].

II. Another type of CCS technology is pre-combustion capture, which involves capturing carbon dioxide before a combustion process produces it. This method is often used in conjunction with gasification processes, where carbon-containing fuels are converted into a synthesis gas that can be used to produce electricity or other products. Pre-combustion capture typically involves separating the carbon dioxide from the synthesis gas before it is combusted, allowing for more efficient capture and storage of emissions [16].

III. Oxyfuel combustion is another type of carbon capture technique, which involves burning fossil fuels in a mixture of oxygen and recycled CO_2 instead of air. This results in a flue gas stream of predominantly CO_2, which can be easily captured and stored. Oxyfuel combustion has the potential to achieve high capture rates and reduce the cost of CO_2 capture, but it requires significant modifications to existing combustion systems and infrastructure [17].

IV. Chemical Looping Combustion (CLC) is a process in which oxygen is supplied to a fuel through a solid oxygen carrier rather than air. This separates carbon dioxide CO_2 from the rest of the combustion products, making it easier to capture and store. On the other hand, Membrane-based capture technology uses membranes to selectively separate CO_2 from flue gas, allowing for its capture before it is released into the atmosphere. One of the critical advantages of CLC is its ability to capture CO_2 without the need for expensive and energy-intensive separation processes. By using a solid oxygen carrier, CLC can effectively capture CO_2 while still producing energy. This makes it a promising technology for reducing emissions from power plants and other industrial processes. Additionally, CLC can be easily integrated into existing power plants, making it a cost-effective option for reducing emissions [18].

V. On the other hand, Membrane-based capture technology offers a more flexible approach to CO_2 capture. By using membranes to separate CO_2 from flue gas selectively, this technology can be tailored to specific applications and operating conditions. Membrane-based capture technology is also energy-efficient, making it a viable option for reducing emissions from power plants and other industrial processes [19].

VI. Cryogenic carbon capture involves the separation of CO_2 from flue gas by cooling it to very low temperatures, typically below -78.5°C, where CO_2 becomes a liquid. The captured CO_2 can then be stored or utilized in various industrial processes. Cryogenic carbon capture has the advantage of high-purity CO_2 capture and can be easily integrated into existing industrial processes. However, the cooling process requires significant energy, making it less cost-effective than other carbon capture methods [20].

VII. Direct Air Capture (DAC) technology involves capturing CO_2 directly from the atmosphere using chemical processes or sorbents. This method has the advantage of being able to capture CO_2 from any source, not just industrial emissions. DAC has the potential to be a scalable and cost-effective solution for reducing CO_2 emissions, but it currently faces challenges related to high energy consumption and cost [21].

VIII. Calcium looping is a carbon capture technology that uses Calcium Oxide (CaO) as a sorbent to capture CO_2 from flue gas. The process involves the reaction of CaO with CO_2 to form Calcium Carbonate (CaCO3), which can then be separated and stored or utilized. Calcium looping has the advantage of being a low-cost and energy-efficient method of carbon capture, but it requires a constant supply of CaO and produces a significant amount of waste [22].

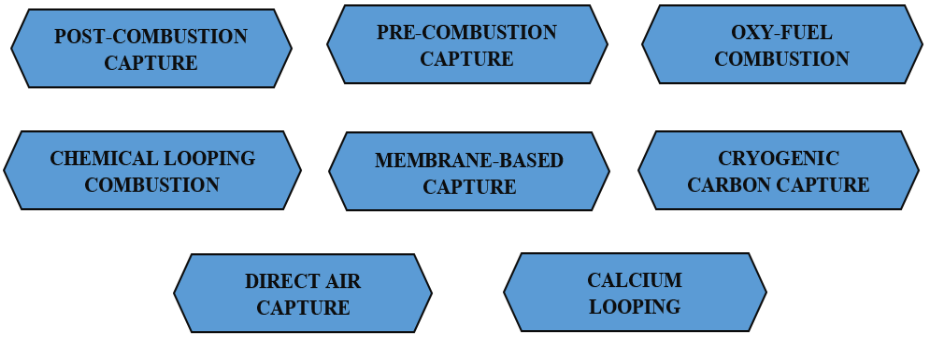

Fig. 1. Classification of CCS technology.

Various types of carbon capture techniques are being developed and implemented to reduce CO_2 emissions from industrial processes and power generation. Each of these techniques has its own advantages and limitations, and the choice of technology will depend on factors such as the type of facility, the concentration of CO_2 emissions, and the cost of implementation. As the global community continues to address the challenges of climate change, it is essential to continue researching and investing in carbon capture technologies to reduce greenhouse gas emissions significantly. The classification of CCS technologies is presented in *Fig. 1*.

5 | General Procedure for CCS

The general procedure for CCS involves capturing CO_2 emissions from industrial sources, transporting the captured CO_2 to a storage site, and injecting it underground for long-term storage or storing it underground in geological formations (see *Fig. 2*). The general procedures for CCS are outlined as follows:

I. The first step in the CCS process is capturing CO_2 emissions from industrial sources such as power plants, cement factories, and refineries. There are several methods for capturing CO_2, including post-combustion capture, pre-combustion capture, and oxyfuel combustion. Post-combustion capture involves separating CO_2 from the flue gas after combustion, while pre-combustion capture involves converting fossil fuels into a mixture of hydrogen and CO_2 before combustion. Oxyfuel combustion involves burning fossil fuels in a mixture of oxygen and recirculated CO_2 to produce a concentrated stream of CO_2 [23].

II. Once the CO_2 has been captured, it must be transported to a storage site. This can be done using pipelines, ships, or trucks, depending on the distance between the capture and storage sites. Pipelines are the most common method of transportation for large-scale CCS projects, as they are cost-effective and efficient. Ships and trucks are typically used for smaller-scale projects or when pipelines are not feasible.

III. The final step in the CCS process is storing the captured CO_2 underground in geological formations such as depleted oil and gas reservoirs, saline aquifers, and coal seams. These formations are typically located several kilometres below the Earth's surface and are sealed by impermeable rock layers to prevent CO_2 from escaping. Once the CO_2 has been injected into the storage site, it is monitored to ensure that it remains trapped underground and does not pose a risk to the environment or human health [24].

While CCS has the potential to reduce CO_2 emissions and mitigate the impacts of climate change, some challenges must be addressed to ensure its success. Further research and development are needed to improve the efficiency and cost-effectiveness of CCS technology and to address concerns about its long-term viability.

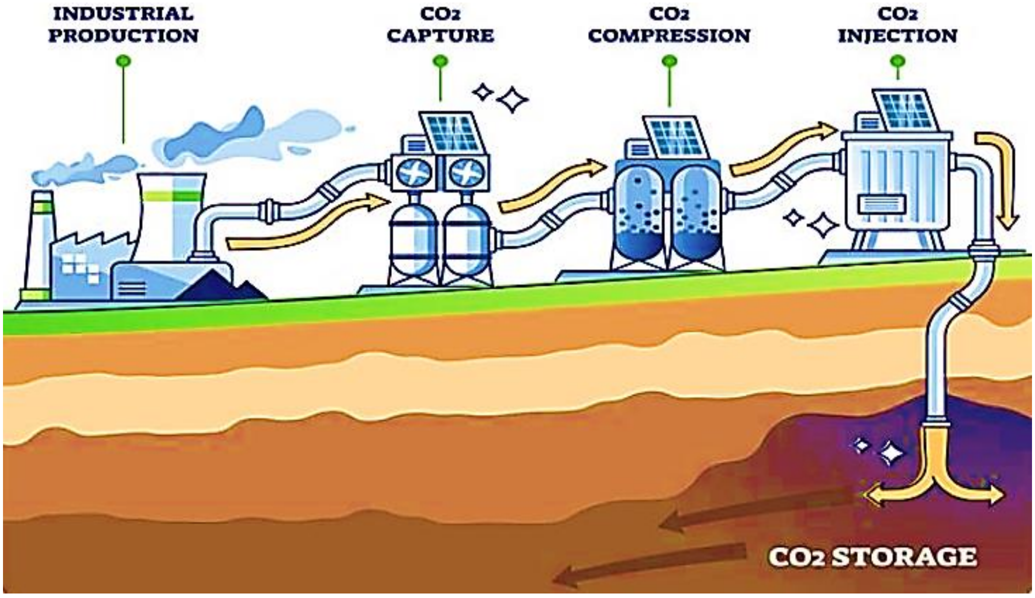

Fig. 2. Illustration of a general procedure for CCS [25].

6 | Methods for Transporting Captured CO_2 to Storage Sites

Transporting captured CO_2 to a storage site is crucial in CCS technology. Various technologies are available for transporting CO_2, each with advantages and limitations. The critical technologies for transporting captured CO_2 to a storage site are outlined as follows:

I. One of the most common methods for transporting captured CO_2 is through pipelines. CO_2 pipelines are similar to natural gas pipelines and can transport large volumes of CO_2 over long distances. Pipelines are a cost-effective and efficient way to transport CO_2, especially for large-scale CCS projects. However, building and maintaining pipelines can be expensive, and challenges are associated with securing rights-of-way and obtaining permits for pipeline construction [26].

II. Another technology for transporting captured CO_2 is by ship. CO_2 can be transported in liquid form on specially designed ships, similar to Liquefied Natural Gas (LNG) carriers. Shipping CO_2 can be a flexible and cost-effective option for transporting CO_2 to storage sites near waterways. However, there are concerns about the safety and environmental risks associated with shipping CO_2 and the potential for CO_2 leakage during transport.

III. Trucking and rail transport are also used for transporting captured CO_2, especially for smaller-scale CCS projects or for transporting CO_2 over shorter distances. Trucks and railcars can transport CO_2 in either liquid or compressed form. While trucking and rail transport are more flexible than pipelines or ships, they are also more expensive and less efficient for large-scale CO_2 transport [27].

Investing in technologies for transporting captured CO_2 to storage sites is essential for the widespread deployment of CCS technology and for achieving global climate goals. Each transportation method has its advantages and limitations, and the choice of technology will depend on factors such as project scale, distance to storage site, and cost considerations. Governments, industry, and research institutions should continue to develop and improve CO_2 transportation technologies to make CCS more viable and cost-effective. The transportation of CO_2 through pipelines or ships is illustrated in *Fig. 3*.

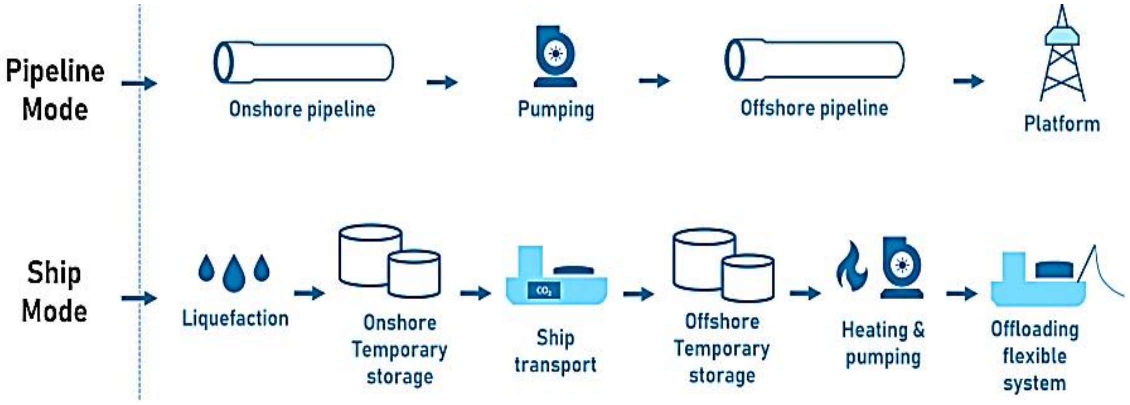

Fig. 3. Illustration of the CO_2 transportation process through pipelines or ships [28].

7 | Methods for Storing Captured CO_2

Various technologies have been developed to store captured CO_2 in a storage site or facility. These technologies play a crucial role in mitigating the effects of climate change by reducing the amount of CO_2 released into the atmosphere. In this study, the most commonly used technologies for storing captured CO_2 are as follows:

I. One of the most widely used technologies for storing captured CO_2 is geological storage. This involves injecting CO_2 into underground geological formations such as depleted oil and gas reservoirs, saline aquifers, and coal seams. The CO_2 is stored in these formations through a process known as mineralization, where the CO_2 reacts with minerals in the formation to form stable compounds. Geological storage has been proven to be a safe and effective method for long-term storage of CO_2 [29].

II. Another technology for storing captured CO_2 is Carbon Capture And Utilization (CCU). This involves capturing CO_2 from industrial sources and converting it into valuable products such as fuels, chemicals, and building materials. CCU helps reduce CO_2 emissions and creates economic opportunities by turning a waste product into a valuable resource [30].

III. A third technology for storing captured CO_2 is CCS. This involves capturing CO_2 from industrial sources and storing it in underground formations. CCS has the potential to significantly reduce CO_2 emissions from power plants and other industrial sources, making it a key technology for combating climate change [31].

The aforementioned technologies offer promising solutions for storing captured CO_2 in storage sites or facilities. Geological storage, CCU, and CCS are all effective methods for reducing CO_2 emissions and mitigating the effects of climate change. By implementing these technologies on a larger scale, significant progress can be made towards a more sustainable future.

8 | Policies Related to CCS

CCS is a crucial technology in the fight against climate change, as it allows for the capture of CO_2 emissions from industrial processes before they are released into the atmosphere. Various policies have been implemented worldwide to promote the development and deployment of CCS technology. These include the following:

I. One such policy is the carbon pricing mechanism, which puts a price on carbon emissions to incentivize companies to reduce their emissions or invest in CCS technology. For example, the European Union Emissions Trading System (EU ETS) is the largest carbon market in the world, covering over 11,000 power plants and industrial facilities. Companies must purchase permits for their emissions, creating a financial incentive to reduce emissions or invest in CCS technology [32].

II. Another CCS-related policy is government funding and support for research and development. Many governments around the world provide funding for CCS projects, either through direct investment or through tax incentives and grants. For example, the United States Department of Energy has funded CCS research and development through programs such as the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) and the Carbon Utilization Program.

III. Some governments have implemented regulations requiring companies to reduce carbon emissions or invest in CCS technology. For example, the UK government has set legally binding targets to reduce carbon emissions by 80% by 2050, and companies must report their emissions and take action to reduce them. Failure to comply with these regulations can result in fines or other penalties [33].

Various CCS policies have been implemented worldwide to promote developing and deploying this crucial technology. While progress has been made, more must be done to accelerate the deployment of CCS technology and reduce carbon emissions. By continuing to support research and development, providing financial incentives, and implementing regulations, governments can help to combat climate change and protect the environment for future generations.

9 | Factors Affecting the Implementation of CCS

Incentives play a crucial role in promoting the adoption of CCS technology, but the following variety of factors can influence the effectiveness of these incentives:

I. The level of financial support provided: CCS technology is still in the early stages of development and deployment, and as such, it requires significant financial investment. Incentives that provide substantial financial support can help offset the high costs associated with CCS projects and encourage more companies to invest in this technology. However, if the level of financial support is insufficient, it may not be enough to incentivize companies to adopt CCS technology, leading to a limited impact on reducing emissions [9].

II. The regulatory environment: regulations play a crucial role in shaping the market for CCS technology, as they can create a level playing field for companies and provide certainty for investors. Incentives aligned with existing regulations and policies can help create a supportive environment for CCS technology while conflicting or inconsistent regulations can hinder the adoption of CCS technology. Therefore, policymakers need to consider the regulatory landscape when designing incentives for CCS technology [34].

III. The availability of infrastructure and resources can also impact the implications of CCS incentives. CCS projects require access to suitable geological storage sites and the necessary infrastructure for capturing, transporting, and storing CO_2. Incentives that support the development of infrastructure and resources can help overcome these barriers and facilitate the deployment of CCS technology. However, if these resources are limited or unavailable, it can hinder the implementation of CCS projects, regardless of the incentives provided.

IV. The high costs associated with its implementation: the construction and operation of CCS facilities require significant financial investment, making it difficult for many companies and governments to justify the expense. In addition, the uncertain economic viability of CCS projects has deterred potential investors from committing to these initiatives. Without sufficient funding and financial support, the development and deployment of CCS technology will continue to be limited, hindering its potential to make a meaningful impact on reducing carbon emissions [4].

V. Regulatory uncertainty has also posed a significant challenge to implementing CCS initiatives. The lack of clear and consistent regulations governing CCS projects has created uncertainty for companies and governments looking to invest in this technology. Without a stable regulatory framework, stakeholders are hesitant to move forward with CCS projects, fearing potential legal and regulatory challenges that could arise in the future. This uncertainty has further complicated the complex process of developing and deploying CCS technology, making it difficult for stakeholders to navigate the regulatory landscape and ensure compliance with relevant laws and regulations [35].

VI. Public opposition: this has also emerged as a significant barrier to the success of CCS initiatives. Many communities and environmental groups have raised concerns about the potential risks and impacts of CCS technology, including the potential for leaks and accidents that could harm human health and the environment. As a result, public opposition to CCS projects has grown, making it difficult for companies and governments to secure the necessary permits and approvals to move forward with these initiatives. Without the support and acceptance of local communities and stakeholders, the development and deployment of CCS technology will continue to face significant challenges and obstacles [36].

Various factors, including financial support, the regulatory environment, and the availability of infrastructure and resources, influence CCS incentives' implications. To maximize the impact of CCS incentives, a comprehensive approach is needed that considers these factors and addresses the barriers to adopting CCS technology. By considering these factors and designing incentives tailored to the CCS industry's specific needs, policymakers can help accelerate the deployment of CCS technology and achieve significant reductions in greenhouse gas emissions.

10 | Environmental Impacts Associated with CCS

While CCS technology has the potential to reduce greenhouse gas emissions and combat climate change, there are concerns about its environmental impacts, some of which are outlined as follows:

I. One of the main environmental impacts of CCS initiatives is the potential for leakage of stored carbon dioxide. If carbon dioxide leaks from storage sites, it can pose risks to human health and the environment. Studies have shown that carbon dioxide leakage can contaminate groundwater, soil, and air, negatively impacting ecosystems and biodiversity. Additionally, carbon dioxide is a greenhouse gas that can contribute to global warming if released into the atmosphere, negating the benefits of CCS initiatives [11].

II. Another environmental impact of CCS initiatives is the energy and resource requirements for capturing, transporting, and storing carbon dioxide. Capturing carbon dioxide from industrial emissions requires significant energy inputs, which can increase overall energy consumption and greenhouse gas emissions. Additionally, the construction and operation of CCS infrastructure require resources such as water, land, and materials, which can have negative impacts on ecosystems and local communities [37].

III. Concerns exist about the long-term stability and security of carbon dioxide storage sites. If stored carbon dioxide leaks or escapes over time, it can have detrimental effects on the environment and human health. Additionally, there is a lack of regulatory frameworks and monitoring systems to ensure the safe and effective storage of carbon dioxide, raising concerns about the potential risks associated with CCS initiatives [5].

While CCS initiatives have the potential to reduce greenhouse gas emissions and combat climate change, there are significant environmental impacts that need to be considered. It is essential to carefully assess the risks and benefits of CCS technology and implement robust regulatory frameworks to ensure the safe and effective storage of carbon dioxide. Additionally, further research and development are needed to address the environmental impacts of CCS initiatives and improve the sustainability of CCS technologies. Sources and impacts of CO_2 leakage from geological sequestration sites are presented in *Fig. 4*.

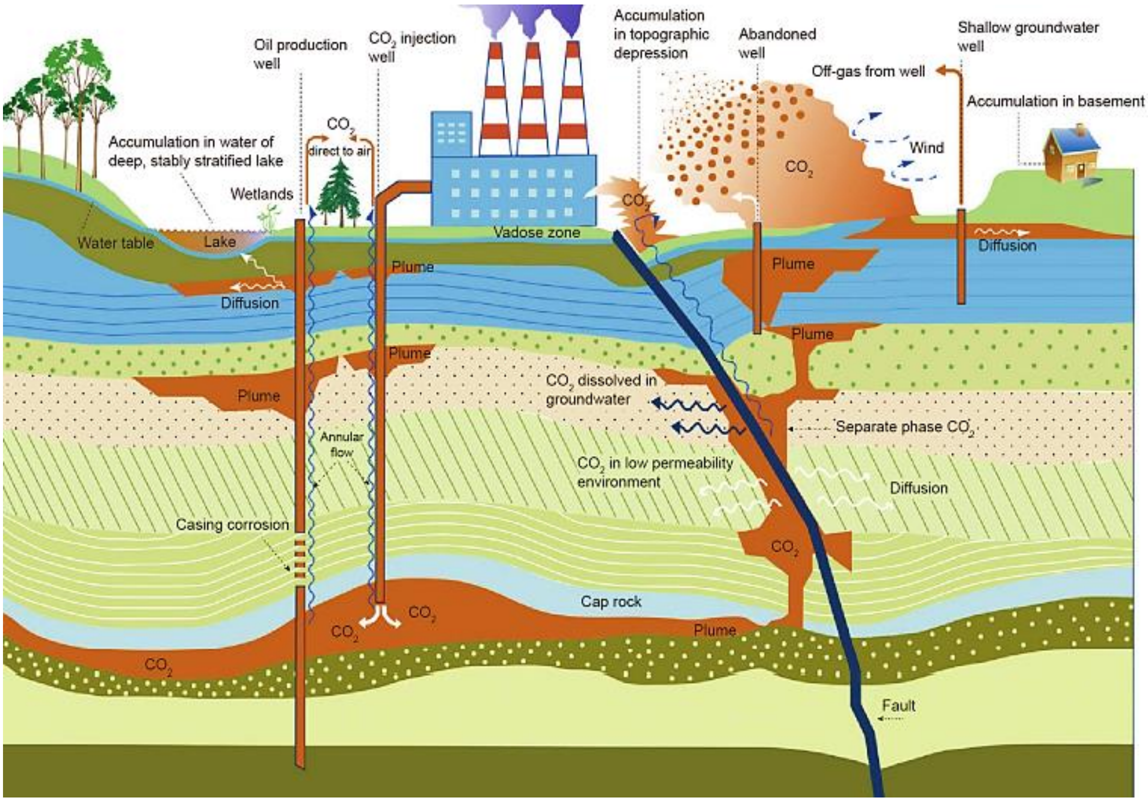

Fig. 4. Sources and impacts of CO_2 leakage from geological sequestration sites [38].

11 | Applications of CCS

Various critical applications of CCS can help mitigate the impacts of climate change and transition towards a more sustainable future. These include the following:

I. One key application of CCS is in the power generation sector. Many power plants, particularly those that rely on fossil fuels such as coal and natural gas, are significant sources of CO_2 emissions. By implementing CCS technology in these plants, it is possible to capture and store the CO_2 emissions before they are released into the atmosphere. This can significantly reduce these power plants' carbon footprint and help meet emissions reduction targets [39].

II. Another vital application of CCS is in the industrial sector. Industries such as cement, steel, and chemical production are also significant sources of CO_2 emissions. By implementing CCS technology in these industries, capturing and storing the CO_2 emissions generated during production is possible. This can help reduce these industries' overall carbon footprint and contribute to global efforts to combat climate change [40].

III. CCS can also be applied in the transportation sector. While electric vehicles and other forms of clean transportation are gaining popularity, many vehicles on the road still rely on fossil fuels. By implementing CCS technology in vehicles or fuel production processes, capturing and storing the CO_2 emissions generated during combustion is possible. This can help reduce transportation's carbon footprint and contribute to efforts to reduce greenhouse gas emissions [41].

IV. In addition to these critical applications, CCS can also be used in other sectors, such as agriculture and waste management. For example, CCS technology can capture and store CO_2 emissions from agricultural practices such as livestock farming or waste management processes such as landfill gas capture. By implementing CCS in these sectors, it is possible to reduce greenhouse gas emissions further and contribute to a more sustainable future [42].

CCS is a crucial initiative in the fight against climate change, and various critical applications of CCS can help mitigate the impacts of climate change. By implementing CCS technology in sectors such as power generation, industry, transportation, agriculture, and waste management, it is possible to significantly reduce greenhouse gas emissions and transition towards a more sustainable future. Governments, industries, and individuals must work together to support and invest in CCS initiatives to achieve our emissions reduction targets and combat climate change effectively.

12 | Approaches for Mitigating Leakage of Stored CO_2

One of the significant concerns with CCS is the potential for leakages of stored CO_2 back into the atmosphere. Various trapping mechanisms can be employed to mitigate this risk and ensure the long-term storage of CO_2. The different trapping mechanisms include structural trapping, residual trapping, dissolution trapping, and mineral trapping, which are outlined as follows:

I. Structural trapping refers to the physical containment of CO_2 within a geological formation, such as a porous rock or a salt dome. This trapping mechanism relies on the impermeability of the surrounding rock to prevent the upward migration of CO_2. Studies have shown that structural trapping can be highly effective in securing CO_2 storage over long periods, with minimal risk of leakage [43].

II. Residual trapping, on the other hand, involves the retention of CO_2 within the pore spaces of a geological formation after injection. This trapping mechanism relies on the capillary forces within the rock to immobilize the CO_2, preventing it from migrating upwards. Residual trapping is considered a reliable method for long-term storage of CO_2, as it can significantly reduce the risk of leakage [44].

III. Dissolution trapping occurs when CO_2 dissolves in the formation fluids, such as water or brine, and becomes trapped within the pore spaces of the rock. This trapping mechanism is particularly effective in saline aquifers, where the dissolved CO2 can be securely stored for thousands of years. Dissolution trapping is considered an essential mitigation technique for leakages of stored CO_2, as it provides an additional layer of security against upward migration [45, 46].

IV. Mineral trapping involves the conversion of CO_2 into stable mineral forms, such as carbonates, through chemical reactions with the surrounding rock. This trapping mechanism is a natural process that occurs over geological timescales but can be accelerated by injecting reactive materials into the storage formation. Mineral trapping is considered to be a highly effective method for long-term storage of CO_2, as the converted minerals act as a permanent seal against leakages [47].

The combination of structural trapping, residual trapping, dissolution trapping, and mineral trapping provides a comprehensive approach to mitigating leakages of stored CO_2 in CCS projects. These trapping mechanisms offer multiple layers of security against upward migration and ensure the long-term storage of CO_2 in a safe and environmentally responsible manner. By implementing these mitigation techniques, the risks associated with CCS can be effectively managed, allowing for the continued development and deployment of this critical technology in the fight against climate change.

13 | Conclusion

Implementing CCS technologies is crucial for averting environmental impacts and promoting a sustainable green environment. This study has shown that CCS can significantly reduce greenhouse gas emissions and mitigate climate change. By capturing carbon dioxide emissions from industrial processes and power plants, CCS can help to prevent the release of harmful pollutants into the atmosphere. Furthermore, the implementation of CCS can also help to promote sustainable development by providing a means of reducing carbon emissions while still allowing for economic growth. By investing in CCS technologies, countries can work towards achieving their climate goals while also supporting the growth of clean energy industries. The findings from this study on the implementation of CCS highlight the importance of this technology in addressing environmental challenges. By developing a framework for promoting the widespread adoption of CCS, policymakers can help to create a more sustainable and green environment for future generations. Continued implementation of CCS technologies must be prioritized to mitigate the impacts of climate change and create a more sustainable future for all. The following recommendations are suggested to promote a sustainable green environment in light of the aforementioned findings.

I. Policy support: governments should provide robust policy support for implementing CCS technology. This includes financial incentives, regulatory frameworks, and long-term commitments to support the development and deployment of CCS projects.

II. Public awareness: there is a need to increase public awareness and understanding of CCS technology. Public perception plays a crucial role in the success of CCS projects, and efforts should be made to educate the public about the benefits and safety of CCS technology.

III. Collaboration: collaboration between governments, industry, and research institutions is essential for successfully implementing CCS projects. This includes sharing knowledge, resources, and best practices to accelerate the development and deployment of CCS technology.

IV. Research and development: continued investment in research and development is necessary to improve the efficiency and cost-effectiveness of CCS technology. Research should focus on developing new technologies, improving existing processes, and reducing the environmental impacts of CCS projects.

V. Monitoring and verification: robust monitoring and verification systems should be put in place to ensure the safe and effective operation of CCS projects. This includes monitoring CO_2 storage sites, tracking emissions reductions, and verifying the environmental benefits of CCS technology.

VI. Stakeholder engagement: engaging with stakeholders, including local communities, environmental groups, and industry partners, is crucial for successfully implementing CCS projects. Stakeholders should be involved in decision-making, and their concerns should be addressed transparently and inclusively.

By following the recommendations outlined in this study, governments, industry, and research institutions can work together to accelerate the development and deployment of CCS projects. This will help reduce greenhouse gas emissions and create a cleaner and more sustainable future for future generations.

List of Abbreviations

Not applicable.

Funding

The research reported in this manuscript was self-sponsored.

Conflict of Interest

There are no Conflict of Interestto declare concerning the content of this manuscript

Author Contributions

Aniekan Essienubong Ikpe led the conceptualization and design of the study, and was primarily responsible for drafting the manuscript. Imoh Ime Ekanem conducted the analysis, contributed to the interpretation of findings, and assisted in revising the manuscript. Kufre Rechard Ekanem was involved in the literature review, data visualization, and final proofreading of the manuscript. All authors read and approved the final version of the manuscript.

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