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Carbon Capture, Utilization, And Storage: Assessing Technological Advancements And Implementation Strategies In The Fight Against Climate Change

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Abstract :-A world where carbon capture, usage and storage effectively ends climate change, a package of technologies being assembled to capture CO2 emissions before they become air pollution (and waste), convert it to something useful, or safely store it underground. This isn't some far-fetched dream. Whether it is the cleaning of fuels before burning them, the cleaning of emissions after they exit the smokestack, or burning the fuel with pure oxygen so the CO2 is much easier to collect, we are getting smarter about CO2 capture because new materials and technologies are being explored. Then once we've captured that CO2, there are many applications, from aiding in the extraction of heavier oil, new compounds, and even mineralizing it into rocks.For the CO2 we do not use right away, deep geological storage can provide a secure long-term home. In sectors where a high carbon intensity is important, such as cement, steel and energy sectors, CCUS is already having a demonstrable effect. In conjunction with emergent, cutting-edge AI and machine learning capabilities, CCUS is already innovating and further streamlining these processes, while still keeping the supply chain safe and efficient. In order for CCUS to take a prominent role and be the backbone of our climate strategy, it will need synergistic policies, smart economic incentives, and stable regulatory landscapes. There will be socio-economic, socio-political and socio-infrastructural challenges to overcome; however, considering the nature of the environment, the combined systemic development of CCUS and renewable energy is an enormous opportunity to fulfill targets toward net-zero emissions and to ensure a sustainable future..

Keywords: Carbon Capture, Usage, Storage (CCUS), CO2 emissions, Climate change, Net-zero emissions, Renewable energy, Deep geological storage, AI and machine learning, Sustainable future

INTRODUCTION

In the center, the carbon capture process generally uses techniques such as the acquisition of pre-combustion, post-cancellation capture and that is combustion of fuel of ie i.e., each exploiting the distinct chemical and physical processes to isolate CO2 from combustion gas or other emission flows. For example, the post-premium acquisition uses chemical solvents to absorb CO2 following the combustion of fossil fuels, allowing the separation of CO2 for the subsequent transport and storage (IPCC, 2018). These progress in separation technologies underline the importance of the science of materials and the development of efficient sorbes and catalysts, which play a crucial role in improving performance and reducing the costs of capture systems. The use of CO2 captured has gained notoriety as a means of closing the carbon cycle.

Innovative approaches such as carbon mineralization, in which CO2 is converted into stable mineral carbonates and the synthesis of fuels, chemicals and CO2 materials, are actively studied and implemented. These applications not only help to mitigate climate change by reducing carbon emissions, but also create new economic opportunities in it by promoting a circular economy. An emphasis on CO2 use technologies illustrates the double advantage of reducing dependence on fossil resources by promoting sustainability through a new generation of resources. The storage component of the CCCs, which involves the geological seizure of CO2 in impoverished oil and gas basins or gas bacins, plays a deep saline, plays an equally critical role. The selection of adequate storage sites depends on in -depth geological assessments to ensure safety and permanence. In addition, recent progress in monitoring technologies have improved trust in long -term storage solutions, providing data necessary for regulatory compliance and public acceptance. These progress therefore strengthen the trust that CO2 can be firmly stored, reducing the potential of losses and other environmental concerns. An effective implementation of CCUS technologies requires not only technological progress, but also policies and support paintings that encourage distribution. In addition, involving the interested parties throughout the sector and communities can encourage essential collaborative efforts to reduce these technologies effectively. As the world passes towards an economy with low carbon emissions, the integration of CCUs in energy policies and climatic action strategies will be fundamental. The forward path highlights the exigent need for continuous innovation and investments in CCUS technology, positioning it as a fundamental tool in the global research of climatic stabilization and sustainable development., Carbon capture, use and storage (CCUS) covers a set of technologies designed to mitigate climate change, addressing increasing concentrations of carbon dioxide (CO2) in the atmosphere. This section provides an overview of the scientific principles underlying CO2 capture, use and storage processes, highlighting the chemical and physical mechanisms that facilitate these advances.

METHOD:

CO2 capture is mainly achieved through three distinct methods: pre-commenced capture, post-commence capture and fuel combustion oxy. Precoming capture involves conversion of fossil fuels into a mixture of hydrogen and CO2, with subsequent CO2 separation before combustion (Nwabueze & Leggett, 2024). This approach usually employs gasification or renovation processes, where CO2 can be removed using physical or chemical solvents such as amines or metallic oxides. Post-regulations capture, the most prevalent CCUS approach, operates with the principle of extracting CO2 from combustion gases emitted after fossil fuel combustion. This is usually achieved with absorption techniques using liquid amines, which react selectively with CO2.

Two primary copies for the use of CO2 are the improved oil recovery (EOR) and the production of chemicals or fuels. This often happens through clever **catalytic processes**, where special materials help speed up the reactions.

The final component of CCUS, storage, involves the long -term CO2 sequence in geological formations. Carbon dioxide can be injected into exhausted oil and gas reservoirs, deep saline aquifers or tireless coal seams, where they can be arrested and contained. The storage process is governed by physical and chemical mechanisms, including hair capture, solubility and mineralization capture, where CO2 reacts with minerals to form stable carbonate minerals on geological time scales (Nwabueze & Leggett, 2024). The appropriate geological formations for storage must have adequate permeability and sealing capacity to avoid leaks, making the characterization of the site and the assessment of essential risks for effective implementation. In general, advances in CCUS technologies are anchored in a robust understanding of chemical and physical principles that govern CO2 capture, use and storage. Research and development in progress, driven by innovative engineering and scientific advances, continue to improve the effectiveness and sustainability of these vital technologies to address the global challenge of climate change., Capture, use and storage technologies (CCU) of carbon represent a critical route to the attenuation of climate change effects by reducing atmospheric carbon dioxide levels (CO2). The scientific principles underlying these technologies depend on the capture of CO2 emissions produced from various sources, its transformation into usable products and its long-term forcible confinement to prevent its start in the atmosphere. At the heart of carbon capture technology are several methods that can be classified as a pre-combustion, post-combustion and oxy-combustion combustion process. The capture of pre-combustion consists in converting fossil fuels into a mixture of hydrogen and CO2, followed by the separation of CO2 before combustion. Post-combustion capture, on the other hand, targets combustion gases emitted by burning fossil fuels, in which CO2 is absorbed using solvents such as Amine solutions. Oxy-fuel combustion has aroused interest due to its operation in a pure oxygen environment, resulting in a concentrated CO2 flow which can be easily captured.

The world of materials science has been a game-changer, giving us smarter sorbents and solvents that make carbon capture both more efficient and less expensive. But the focus has really shifted beyond just capturing CO2; now, we're all about turning that captured waste into valuable products. This "carbon utilization" means we can transform CO2 into a whole range of things, like sustainable fuels, useful chemicals, and even carbonates. Think about it: we can take CO2 and, through clever catalytic processes, convert it into methanol or methane, helping us produce fuels that are much kinder to our planet.In addition, the incorporation of CO2 in concrete production has a double advantage by kidnapping CO2 while simultaneously improving the properties of concrete material.

Biotechnological methods that use microorganisms or algae to change CO2 are also making significant progress in using nature itself to fight the gas. There is great promise for these little powerhouses to produce sustainable biofuels and valuable biochemical. But no matter how we use the captured CO2, **safe and permanent storage** remains absolutely vital in CCUS technology, ensuring that all that effort prevents CO2 from ever reaching our atmosphere.

The underlying scientific principle of geological storage implies the injection of CO2 in deep geological formations such as the exhausted oil and gas reservoirs, saline aquifers and coal seams with impressive. In -depth research has elucidated key factors concerning the safety and integrity of long -term storage, including the monitoring of potential leakage routes and geochemical interactions between CO2 and surrounding geological material

Our confidence in storing CO2 safely underground has really grown thanks to the latest **surveillance techniques**, like detailed **satellite imaging** and advanced **geophysical surveys**, which help us confirm how well these geological sites are performing. And when it comes to putting CCUS into practice, its reach is broad, applying to various heavy-hitting industrial sectors. We're talking about industries that have traditionally spewed a lot of carbon, like **electricity generation**, **cement production**, and **steel manufacturing**, all of which can now benefit from these emission-cutting technologies.

While industries strive from net-zero objectives, the implementation of CCUs has become a vital strategy, public acceptance and commitment are crucial for the successful deployment of CCUS initiatives, requiring transparent communication on the risks, advantages and importance of continuous research in the effective attenuation of climate change., Carbon capture technologies can be classified into three main categories based on their operating times compared to the combustion process: pre-cancellation capture, post-combustion capture and fuel combustion for bones. Each category uses distinct scientific principles and offers specific practical applications relevant to the various industrial processes.

The resulting CO2 can therefore be separated, allowing the hydrogen to be composed with a significantly lower carbon imprint. This approach has been implemented in various pilot projects, such as the Petra Nova project in Texas, which captures about 1.6 million tons of CO2 every year from an electric coal power plant (Osman et al., 2021). Post-bustion capture is the most commonly used method, in particular in existing energy generation structures.

The significant implementations of post-premium capture technologies include the Dam Dam project in Canada, which integrates the capture systems in an existing coal power plant, successfully capturing over 1 million tons of CO2 per year (Osman et al., 2021).

The combustible combustion systems for oxy allow electrical plants to obtain greater efficiency in the capture and storage of CO2, as well as reducing nitrogen oxides emissions (NOX), a significant polluting associated with conventional combustion. An important illustration of this technology is the Oxyfuel Callide project in Australia, where a pilot plant has effectively shown that fuels for OSSI can be burned to produce electricity (Osman et al., 2021).

RESULT:

The capture of pre-combustion offers high CO2 acquisition rates but is mainly suitable for new structures or significant retrofits, limiting its immediate applicability. On the contrary, post-combustion acquisition technology can be implemented in existing infrastructure, promoting faster distribution. However, the lowest CO2 concentrations in combustion gas can lead to an increase in capture costs. The combustion combustible for Oxy offers an interesting alternative thanks to its high CO2 concentration in the exhaust, but requires changes to current combustion technologies and infrastructures, which can bear additional costs and operational challenges. Understanding these classifications and their respective advantages is essential for politicians and interested parties in charge of guiding the development and deployment of carbon capture technologies to effectively mitigate climate change. The intuitions on these systems will support the strategies in various sectors, guaranteeing a global approach to a sustainable energy future., Recent developments in carbon capture technologies have emphasized the improvement of efficiency and effectiveness in the absorption of carbon dioxide (CO2) through a variety of materials and methods. The Quid of these advances lies in the development of new absorbents that can achieve high selectivity for CO2, resist competitive adsorption of other gases and efficiently operate in variable operational conditions. Traditional amina solvents based, although widely adopted in industrial applications due to their established performance, face limitations regarding energy consumption and degradation. In response, researchers have explored advanced sorbantes, such as Metal-Organic Mark (MOF), Covalent Organic Mark (COF) and next-generation amines. The MOF, characterized by their tunable pores structures and large surface areas, exhibit higher adsorption capabilities for CO2 compared to conventional materials. For example, studies have shown that MOFs can capture CO2 to low -parts pressures, which makes them particularly suitable for fuel -fightering in combustion gas environments (Wilberforce et al., 2021). In addition, the ability to functionalize MOF for improved CO2 selectivity has opened new paths to optimize capture performance. Another promising approach is the use of sorban systems based on Ionogel, which combine the advantages of solid and liquid materials to improve the efficiency of CO2 capture. The Ionogels, which consist of integrated ionic liquid phases within a porous matrix, have shown remarkable CO2 absorption capabilities while minimizing evaporation problems and leaks of solvents associated with conventional solvents. In addition, several studies have quantified the performance of ionogels in a variety of conditions, emphasizing their adaptability in fluctuating environmental environments. Membrane -based separation technologies have also seen significant advances, particularly in the design of facilitated transport membranes that selectively allow CO2 to be promoted while preventing other gas species. The incorporation of ionic or polymeric doptes in traditional polyimide membranes has led to greater permeations and permselectivities of CO2. The research stressed that such membranes could effectively operate in high concentration CO2 environments, further solidifying their role in carbon capture processes. In addition to new materials, innovative process designs have also improved the performance of carbon capture technologies. Process intensification strategies, such as the integration of capture systems with electrical plants or industrial sites, have caused interest. By optimizing the design of these systems, energy sanctions associated with CO2 capture can be reduced significantly. In addition, the use of hybrid capture systems, which combine different methods, such as adsorption and absorption, has demonstrated potential to achieve greater general efficiencies, which underlines the importance of integration of the method in contemporary capture technologies. The research has also underlined the critical role of automatic learning and data analysis to optimize the performance of carbon capture systems. Predictive modeling techniques, informed by experimental data, allow researchers to understand complex interactions within capture processes and adjust the operational parameters for optimal performance. These computational tools are invaluable to identify the most appropriate materials and configurations, which allows greater decision making in the system design and implementation. The scalability of these technological advances remains a primary concern, which requires continuous efforts to make the transition from laboratory scale successes to commercial viability. Effective associations between academia, industry and government can foster innovation roads that unite this gap, promoting the deployment of effective carbon capture solutions. As the field evolves, aligning these advances with economic policies and incentives will be essential to accelerate the adoption of carbon capture technologies, making significant contributions to mitigate climate change., The use of captured carbon dioxide (CO2) presents a promising border to mitigate the environmental challenges raised by climate change. Among the various strategies to use CO2, innovative conversion processes in fuels, chemicals and materials have gained significant attention, allowing a circular economy approach for carbon management (Memon et al., 2024).

Created synthetic natural gas can be injected directly into the gas network or use in applications that cover residential heating to industrial processes. Recent studies indicative of greater catalyst stability and reduced operational temperatures suggest that this method can present a scalable solution for the use of carbon while supporting the transition to a low carbon economy (Memon et al., 2024). To energy carriers, another vital area of CO2 use implies the synthesis of valuable chemicals. CO2 methanol production has attracted a substantial interest, since methanol is not only a fuel but also a construction block for a myriad of chemicals. The research has shown that CO2 can hydrogen itself to produce methanol using advanced catalysts at moderate temperatures and pressures, racing the path for integrated CO2 reduction systems (Memon et al., 2024). The versatility of methanol allows its incorporation into the manufacturing processes of conventional chemicals, creating a path to sustainable chemical production.

The integration of carbon capture and use technologies within existing energy and industrial systems can significantly increase current efforts aimed at mitigating climate change, offering a double benefit by generating economic value while reducing greenhouse gas emissions (Memon et al., 2024)., The techniques of geological kidnapping, oceanic storage and mineralization represent fundamental advances in carbon capture and storage technologies (CCS), each based on different scientific principles that facilitate the long -term kidnapping of CO2. Geological kidnapping implies carbon dioxide injection captured in deep geological formations. This method uses porous rock formations, typically located 800 meters or deeper underground, which have the ability to contain large volumes of CO2. The scientific basis for geological storage depends on the principle of float, in which the injected CO2 behaves like a gas and is contained by waterproof cover that avoid their migration to the surface (Zhao et al., 2023). The scientific principle here is based on the ability of the ocean to dissolve the gaseous CO2, as well as its storage in the form of carbonic acid, bicarbonate and carbonate ions. This method could theoretically kidnap billions of tons of CO2, taking advantage of the ocean currents and stratification to disperse and treat injected carbon (Zhao et al., 2023). However, oceanic storage is not exempt from risk.

Regulatory measures should consider both ecological impacts and the benefits of increasing carbon kidnapping. Mineralization techniques imply CO2 conversion into stable mineral forms through natural geological processes, such as carbonate mineralization. This approach exploits the natural weathering processes that kidnap carbon through geological time scales, emphasizing the sustainable long -term carbon storage potential. The current challenge lies in climbing this technology; Reaction speeds are often too slow in environmental conditions, and conducting the process requires significant energy entry and specific reagents. A notable case study is that of the Heidelbergcement Phare Project in Norway, which integrates carbon capture into cement production to considerably reduce emissions. The process consists in capturing CO2 from combustion gas using amine -based solvents and subsequently in the suite in stable carbonates, facilitating both the capture and storage of CO2 (Nagireddi et al., 2023). In the steel sector, CCU progress is crucial to approach industry dependence on production methods with high carbon intensity. The implementation of carbon capture technologies, such as the use of integrated gas grassification cycle systems (IGCC), presents a promising approach. For example, the Hisarna process developed by Tata Steel effectively incorporates the treatment of iron ore and carbon gas, capturing CO2 at the source. The pilot factory in the Netherlands has successfully demonstrated that around 50% of CO2 emissions can be captured from the steel production process, considerably contributing to the reduction of emissions (Nagireddi et al., 2023).

The dams limit in Canada serves as an exemplary case, where Saskpower has modernized part of its coal plant to capture more than 90% of the CO2 produced. This project not only puts the feasibility of the modernization of the existing infrastructure, but also illustrates the integration of CO2 captured in improved oil recovery operations (EOR), allowing additional sources of income while sequestrating emissions (Nagireddi et al., 2023). The aspect of use of CCUs has led to innovative applications in the production of chemicals, fuels and materials. For example, CO2 is used as a raw material in methanol production, a precious chemical with many applications. Projects such as the carbon capture and use program developed by the Clean Solutions carbon solutions in the United Kingdom show that the marketing of this technology, where CO2 captured from industrial processes is converted into methanol, thus substituting raw materials derived from fossil fuel (Nagireddi et al., 2023). Effective implementation strategies are also evolving, informed by these practical applications. Political decision -makers are increasingly recognizing the importance of regulatory support managers and economic incentives to stimulate the adoption of CCUS technologies. For example, the introduction of carbon pricing mechanisms and tax credits can considerably modify the cost-to-service analysis for companies that are considering CCUS investments.Collaboration between government agencies, research institutes, and industry players is crucial for advancing CCUS technology to meet emission targets. Case studies like Heidelbergcement, Tata Steel, and Saskpower demonstrate the technical viability and financial potential of these technologies in sectors like energy production, steel, and cement.. Case studies by Heidelbergcement, Tata Steel, and Saskpower demonstrate the technical viability and economic potential of these technologies for effective implementation. (Nagireddi et al., 2023). This progress not only reduce emissions but also paves a more sustainable industrial landscape., Integration of automatic learning (ML) and artificial intelligence (IA) in carbon capture, use and storage (CCU) has become a transformative approach to improve efficiency and efficiency in the fight against climate change. By taking advantage of large sets of data and sophisticated algorithms, AI and ML provide a robust predictive modeling and real -time surveillance capacities which optimize various aspects of CCUS technologies (Yan et al., 2021). Basically, automatic learning involves algorithms that can learn and make data -based predictions.

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The mechanisms of financing of multilateral development banks could be fundamental in supporting low -income nations in the development of CCC capacity for their specific economic contexts. Institutional support for the education and development of the workforce is another critical area that requires attention in the CCU political paintings. The initiatives that expand the tertiary and professional training in technology, engineering and environmental carbon capture sciences are essential to build a qualified workforce capable of implementing and maintaining CCU infrastructure. Governments and interested parties in the sector must invest in educational programs for the construction of capacity to ensure that the next generation of professionals is equipped with the technical skills necessary for the flourishing sector of the CCU. A multifaceted approach to politics is essential for the maturation of CCUS technologies. This approach should include financial stimulation, regulatory clarity, international collaboration and the development of the workforce as a key components. By effectively exploiting these strategies, governments can guide the research, development and implementation of CCUS technologies, ultimately supporting global efforts in the mitigation of climate change and sustainability. Investments and innovation continues in this sector will be fundamental in the struggle to balance economic growth with environmental responsibility (GUPTA et al., 2023)., The scaling of capture, use and storage technologies (CCU) of the carbon is faced with several interconnected challenges which hinder wider adoption. These challenges are mainly classified as economic, infrastructural and socio -political barriers, which collectively hinder the effective deployment of essential CCUS solutions to mitigate climate change. Economic challenges represent an important obstacle in the advancement of CCUS technologies. High investment costs associated with the development, installation and operation of CCUS systems are often deemed prohibitive by stakeholders. The integration of carbon capture systems requires considerable initial investments, which can dissuade private and public financing, in particular in low -cost carbon regions or where the fossil fuels industries dominate the economic landscape. In addition, the operating costs in progress linked to energy consumption in the capture processes and the need for maintenance and monitoring systems add another layer of financial load. A lack of economic incentives, such as carbon subsidies or credits, exacerbates these financial problems and dissuade investments in CCUS technologies. Gao et al. (2020) argue that without substantial government support and clear pricing mechanisms for carbon emissions, the economic viability of CCUs remains tenuous. Infrastructural barriers also complicate the scale of CCUS technologies. Socio -political barriers also play a central role in the adoption of CCUS technologies. Public perception and acceptance are essential elements that influence the implementation of CCUS projects. National and regional policies that promote environmental sustainability tend to differ considerably, leading to a disparate landscape for the adoption of CCUs. Gao et al. (2020)

DISCUSSION:

To meet the challenges with multiple facets of economic viability, inadequacies of infrastructure and socio -political acceptance is essential to allow the scaling of CCUS technologies. A concerted effort that includes political innovation, targeted financial strategies, progress in infrastructure and effective community commitment initiatives is necessary to elucidate the way to follow for the adoption of CCUs and its potential role in the fight against climate change., The effective implementation of carbon capture, use and storage technologies (CCUS) is essential to achieve substantial reductions in greenhouse gas emissions. Strategies for successful implementation cover a variety of best practices, participation of interested parties and mechanisms to improve public acceptance. As observed in recent studies (Hammed et al., 2021), a multidimensional approach is crucial to address the technological and socio -political challenges associated with the implementation of the CCU. One of the fundamental strategies for the effective implementation of CCUS lies in the establishment of regulatory frameworks that promote innovation while guaranteeing environmental security and integrity. Policy formulators are encouraged to develop coherent policies adapted to local contexts, integrating CCU within broader climate action plans. This includes establishing clear objectives for carbon reduction, providing tax incentives, such as tax credits or subsidies for the first CCUS technologies users and facilitate funds for research and development activities. Such support regulatory environments can promote private sector investment and technological advances in CCU. The public acceptance of CCUS technologies is critical for their scale implementation. Successful implementation strategies should include transparent communication that transmits both the benefits and risks associated with the CCU. It is essential to address erroneous concepts and concerns, particularly regarding the safety and environmental impacts of carbon storage sites. To commit to the leaders and influencers of the community can also help close the gaps in understanding, cultivating a cooperation environment instead of resistance. The use of visual aid, case studies of successful implementations and technology demonstrations can be used to improve public understanding and acceptance. Finally, promoting a culture of innovation and collaboration between institutions and research industries is essential to promote advances in CCUS technologies. Associations between sector can accelerate the development of new materials and processes, improve carbon uses and improve carbon storage methodologies. Creating incubator programs or innovation centers specifically aimed at CCU can stimulate knowledge exchange and the application of best practices on a global scale. The strategic implementation of CCUS technologies implies a comprehensive and inclusive approach, integrating regulatory support, the participation of interested parties and public dissemination. As the urgency of combating climate change intensifies, the deployment of CCUS effective strategies will be indispensable to achieve global emission objectives and move towards a sustainable future., The environmental impacts of carbon capture, use and storage technologies (CCUS) have become a focal point of research, particularly through the lens of life cycle evaluations (ACLs) that elucidate their roles in carbon mitigation and sustainability

The focus of many studies, such as Peres et al. (2022), it has been to evaluate the entries and exits of energy in these stages, which informs the general carbon footprint of technologies. For example, to evaluate energy consumption associated with capture technologies-incoming absorption, adsorption, and separation of amine-row-based membranes that these processes can be intensive in energy, resulting in a significant carbon penalty if energy is from fossils. In terms of carbon capture, various methodologies such as direct air capture (DAC) and post-compliance capture of industrial processes showed varied environmental results. DAC, although in theory, in theory, usually incurs high operating costs and energy requirements, raising questions about their long -term sustainability unless it is fueled by renewable energy sources. Environmental benefits are maximized when DAC is integrated into renewable energy systems, significantly reducing the overall intensity of carbon compared to traditional fossil fuel energy. The aspect of using CCUS, particularly through the conversion of CO2 captured into chemicals or valuable fuels, also deserves attention in the LCAs. Products such as methanol and urea were identified as potential roads to integrate CO2 captured on more sustainable routes. However, the implications of the life cycle of these conversion processes may vary widely based on the energy inputs and the efficiency of conversion technologies. Comprehensive LCAs show that while use has a promising avenue for carbon mitigation, it should be carefully implemented to minimize recovery effects, where benefits can be compensated for increasing fossil fuel use in the production process. Storage solutions, such as geological kidnapping, are promising for long -term carbon mitigation. The effectiveness and environmental security of storage sites should also be evaluated through the LCAs.Risks of geological formation leaks to carbon storage requires assessment of the integrity of these formations, appropriate local selection, and long-term monitoring strategies. As research continues to inform the potential integrity of geological formations for carbon storage management it is important to understand other aspects in optimizing carbon capture, use and storage (CCUS) technologies with the specific intention of utilizing carbon in a sustainable and mitigative manner. In addition to managing greenhouse gas emissions CCUS technologies would also promote reduction on climate change effects for our future. Nevertheless, it is also important to recognize some gaps in perspective as it effects future assessments and perspectives in CCUS technologies. Future advancements in technological solutions affecting capture may occur when profitability and scalability is achieved. The use of automatic learning in conjunction with other AI methods employed in monitoring and other CCUS systems would likely optimize capture models, forecast operational performance, reduce operational time and deliverables, and fuel model development. Robust algorithms would require significant advancement in order to function on site under various environmental conditions while accurately quantifying the complexities of chemical interactions involved in CO2 capture and storage. As we continue to advance in our understanding of the potential solutions, there are still challenges regarding, site selection, monitoring, long-term safety of storage and additional research requirements.. Variability in geological formations in all regions requires extensive geophysical characterization studies to ensure safe and effective CO2 storage. In addition, advanced monitoring techniques that use remote detection and subsurface image need greater development to guarantee the integrity of storage sites over time (Tiwari et al., 2024). Establishing protocols for risk assessment and public participation remains crucial for community support and regulatory approval for storage projects. The future of CCUS technologies requires a multidimensional approach that encompasses scientific advances, practical applications, socio -political considerations and effective implementation strategies. Addressing these research gaps will be fundamental for the successful scale and the deployment of CCUS, ultimately contributing to international efforts to combat climate change., The integration of acquisition, use and storage technologies (CCU) with renewable energy systems represents a promising strategic approach to reduce carbon emissions while improving energy safety. This integration uses the complementary strengths of both sectors to create synergistic effects, leading to efficient carbon management and sustainable energy production. Like Ganeshan et al. (2023) Highlight, the interaction between CCU and renewable energy can significantly influence the global energy panorama by facing one of the main challenges, such as effectively disacing the production of energy from carbon emissions. Practically, numerous implementations demonstrate the profitability of the coupling of the CCCs with renewable sources. For example, the application of biogas systems coupled with carbon capture allows the treatment of emissions, simultaneously producing energy from waste resources, thus improving the circular economy. In addition, progress is emerging in the hybrid systems that combine the production of hydrogen from renewable electrolisi with carbon capture processes. These additions not only optimize the capture of CO2 during the production of hydrogen, but also facilitate targeted use paths in which CO2 captured can be used in hydrocarbons or chemicals produced briefly, thus creating a carbon cycle without continuity. In addition, effective implementation of these integrated systems requires innovative regulatory paintings and financial mechanisms. As noted by Ganeshan et al. (2023), Support government policies could encourage investments in renewable infrastructures incorporated by CCU, thus promoting adoption. Financial models that remunerate CO2 reductions can provide critical support for projects, increasing their attraction to private investors. In addition, research on new business models, including carbon trade and circular economy, will play an essential role in facilitating the transition to these integrated systems. In facing intermittence challenges associated with renewable energy sources, the integration of energy accumulation solutions becomes crucial. Technologies such as batteries, thermal storage and even advanced solutions such as pumped Hydro can provide the necessary ability to stabilize energy flows. This is particularly relevant when a high renewable energy production coincides with a low demand for energy, allowing to redirect the excess of electricity towards high -demand CCU processes when necessary. The abilities of these storage systems can enhance the operational efficiency of the carbon capture units, rendering them more reactive and tuned for intermittent energy supply.

CONCLUSION:

In the fusion of CCU technology compatible with renewable energy systems presents a layered opportunity to mitigate emissions of carbon while providing a defensive stamina against energy threats. Encouraging resilience of the system, sustainability, and mobility towards a global net-zero economy.While the ongoing research continues to develop these additions, the path to large -scale implementation of CCU technologies in tandem with renewable energy will become increasingly clear., Advances in carbon capture, use and storage technologies (CCUS) highlight a critical moment in the battle ongoing against climate change. As the global community deals with the demands of reducing greenhouse gas emissions, the role of CCUS emerged not only as crucial, but also increasingly sophisticated in its scientific principles and practical applications.The detail of the potential methods that range from adsorption and absorption techniques to novel chemical conversions for use underscore the robustness and versatility of CBUS systems. These developments will be enhanced tapping computational modeling and improved understanding of thermodynamic principles are leading to further accelerated tailored optimization of capture efficiencies while being economically viable. From a practical point of view, the implementation of CCUS technologies covers a diverse variety of sectors, presenting solutions that are not limited to emissions reductions. The use of CO2 captured as a prime matter in the production of chemicals, fuels and construction materials demonstrates the transformative potential of CCUS in circular economy models. The above examples are not only a way of reducing emissions; they are a reinvention of industrial processes so that they consider sustainability objectives.

Addressing the gaps that exist in current CCUS functions requires a multidisciplinary strategy taking into account the technological, social and economic implications of any alterations. Continuous innovation is vital; not only do we have to refine current practices, but we need to start looking for new methods of capturing, using and storing carbon. The integration of CCUs into broader carbon management strategies requires robust dialogue between gym and industry. The evolution of these technologies depends on the ability to promote synergies, where scientific research ideas inform practical applications and sector experiences return feedback that can direct future research. In conclusion, the fight against climate change rests on our ability to innovate within CCUS and all work together as collective changemakers to adopt these technologies widely to make impact. These collaborative efforts would enable the scientific community to close the gap between research and real-world solutions so that CCUS really has the potential not only to help us achieve climate objectives but also to be part of a sustainable future for all. Continuous advocate of policy makers, coupled with industry engagement can help enhance CCUS to help create a cultural shift in how society approaches climate resilience.

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