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Assessment of Carbon Assets and Management Technologies: a Comparative Analysis

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By comparing and evaluating carbon management systems, including DAC, carbon consumption, and mitigation strategies, this study addresses the escalating quantities of atmospheric CO_2 that are contributing to climate change. We evaluate each technology based on its technical sophistication, economic feasibility, and environmental impact using a multi-criteria decision-analysis (MCDA) approach. The assessment approach comprehensively evaluates the advantages and disadvantages of each strategy by utilizing quantitative data and expert commentary. The results indicate that no single technology is capable of achieving all of the carbon mitigation objectives. Consequently, a portfolio-based approach is necessary. The results of this study can be utilized by researchers, policymakers, and corporate executives to identify and implement carbon management strategies that promote sustainable development and mitigate climate change.

1. Introduction

As atmospheric CO_2 levels rise, effective carbon management strategies are crucial for mitigating climate change (Wiedmann and Minx, 2008). Key sources of carbon emissions include industrial processes, energy production, and transportation, which significantly contribute to climate change and environmental degradation (Gailhofer et al., 2021). Addressing these challenges involves various strategies, such as Carbon Capture and Storage (CCS), Direct Air Capture (DAC), and Carbon Utilization (CU) (Ridoutt and Pfister, 2013). CCS captures CO_2 emissions from fossil fuel combustion and stores them in underground geological formations, serving as a potential tool for reducing industrial pollution (Strubell et al., 2019). DAC, which captures CO_2 directly from the air, offers the potential to neutralize emissions. Additionally, CU converts CO_2 into fuels, chemicals, or construction materials, presenting both environmental and economic benefits (Ridoutt et al., 2010). However, these technologies face challenges such as scalability, technical limitations, and high costs. Integrating these technologies with existing infrastructure and securing robust policy support are essential for overcoming these barriers (Stoessel et al., 2012). Assessment of these technologies is necessary to evaluate their strengths and weaknesses and guide decision-makers toward viable solutions. This study employs a Multi-Criteria Decision Analysis (MCDA) approach to assess the environmental impact, economic feasibility, and technological sophistication of each technology. While previous research has utilized MCDA frameworks to evaluate carbon management technologies (Lacoste et al., 2019), this study introduces an innovative framework by integrating expert opinions and quantitative data, addressing gaps in the existing literature. By providing a holistic evaluation of carbon management strategies, this study aims to identify the most effective methods for reducing global carbon emissions and contributing to sustainable CO_2 reduction programs. Previous studies have explored various aspects of carbon management technologies. Ju and Kocaoglu (2014) addressed the contradiction between coal-based electricity and CO_2 emissions, proposing an assessment model for CCS systems in coal-fired power plants. Kubota and Shen (2022) optimized petroleum consumption in hybrid electric vehicles through case studies and cost function analysis, while Ma and Bai (2024) developed a decision-making model for Carbon Dioxide Removal (CDR) technologies using enhanced MULTIMOORA evaluation. Akaa et al. (2016) has shown that AHP/MCDA is advantageous for the examination of support systems in a variety of environmental contexts. The efficacy of AHP in rating renewable energy technology options based on multiple factors was demonstrated by Mastrocinque et al. (2020). Despite these contributions, there remains a need for

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a more integrated and comparative analysis of various carbon management strategies. The literature review identifies significant gaps in current carbon capture assessments, particularly in integrating multi-dimensional criteria and benchmarks for a holistic evaluation. Existing studies often overlook the interplay between technological efficiency and economic viability, which this study aims to address by proposing an improved, multifaceted assessment model. This study aims to bridge these gaps by linking empirical results with a broader literature review and highlighting the effectiveness of different technologies in combating global carbon emissions.

2. Proposed Work

2.1 Development of Assessment Framework

The assessment framework enables a thorough comparison of carbon management methods by considering technical maturity, environmental impact, and economic feasibility. It is crucial to consider the initial investment and continual operational costs for each metric t of CO_2 that is reduced or captured when evaluating the economic feasibility. The environmental impact is assessed by taking into account the direct and indirect capacity of the technology to reduce CO_2 emissions, as well as the emissions that occur during the product's lifespan. The Technology Readiness Level (TRL) monitors the advancement of various technologies and assesses their maturity. Figure 1 illustrates the architecture of the proposed system. A weight is assigned to each criterion in accordance with its relative significance with experts. The final performance score for each technology can be determined by adding the weighted ratings of all the criteria.

$$\mathrm{PS} = W_e \times C_e + W_{en} \times C_{en} + W_{tm} \times C_{tm} \quad (1)$$

where PS is the performance score, and W_e , W_{en} , and W_{tm} are the respective weights for economic, environmental, and technological criteria.

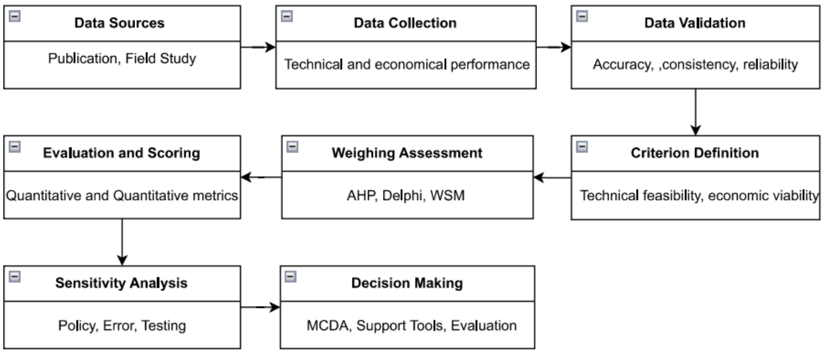

Figure 1: System Architecture

2.2 Selection of Carbon Management Technologies

To select carbon management technology, understanding of CO_2 emission reduction techniques is necessary during the evaluation process. It is crucial to investigate a diverse array of carbon management systems, each with its own advantages and disadvantages, during the decision-making process. Technology focuses on emission reduction, carbon utilization, capture and storage, and direct air capture. CCS, one of the most extensively researched technologies, involves capturing and storing CO_2 from power plants and industrial sources. This method is advantageous for substantially reducing emissions from existing infrastructure. DAC devices, which capture CO_2 directly from the air, offer a solution for emissions from sectors beyond immediate control. DAC's negative emission characteristics are beneficial when source emission reductions are insufficient to meet climate goals. Carbon utilization technologies reduce emissions and generate beneficial products by converting CO_2 into fuels, chemicals, or construction materials, providing financial incentives for carbon management. These technologies can potentially reduce carbon reduction costs and open new markets. The primary objectives of carbon reduction initiatives include enhancing energy efficiency, utilizing renewable energy sources, and optimizing fuel conversion. These solutions have the potential to significantly reduce emissions, especially in the transportation and industrial sectors. The selection process assesses the maturity, scalability, and appropriateness of each technology for current and future carbon management needs.

2.3 Criteria Weighting and Scoring System

The criterion score and weighting mechanism is pivotal in evaluating carbon management technology. This approach utilizes multiple criteria to ensure a balanced and impartial evaluation. The process begins by assigning weights to various assessment criteria, reflecting their significance in the overall evaluation. These criteria include environmental impact, economic feasibility, and technological advancements. The Analytic Hierarchy Process (AHP) or other Multi-Criteria Decision Analysis (MCDA) methods are employed to determine these weights. AHP involves breaking down complex decisions into simpler components and performing pairwise comparisons to assign relative importance to each criterion. This hierarchical approach ensures that all relevant factors are considered and accurately reflected in the final evaluation. AHP facilitates a systematic evaluation by organizing criteria hierarchically and comparing them pairwise. This method allows for the consideration of both quantitative and qualitative factors, ensuring that subjective judgments are incorporated in a structured manner. The criteria weights are derived from expert consultations and literature reviews, ensuring that they align with current industrial and scientific standards. A total of five experts were involved in determining the criteria weights. These experts were selected based on their specialized knowledge in carbon management technologies, academic publications, and professional experience in relevant industries. Benchmarks for the scoring system are based on International Energy Agency (IEA) standards and expert opinions. Once the weights are established, the performance of each technology is assessed against these criteria. Scoring is typically performed on a scale from 1 to 10, where 10 represents exceptional performance and 1 indicates substandard performance. The scoring process involves both quantitative metrics, such as cost per metric t of CO_2 captured, and qualitative assessments, such as regulatory compliance and scalability. Quantitative factors include metrics like energy consumption, cost efficiency, and CO_2 reduction capability. Qualitative factors might involve technology maturity, ease of integration, and environmental regulations compliance. The scores for each criterion are then multiplied by their respective weights to obtain weighted evaluations for each technology. The final performance score for each technology is the sum of its weighted scores across all criteria. This ensures that all relevant factors are considered, providing a clear and objective basis for technology comparison and selection. The weighted rating system facilitates a nuanced understanding of each technology's strengths and weaknesses, guiding decision-makers toward solutions that offer optimal environmental, economic, and technological benefits.

2.4 Data Collection and Analysis

Data was collected from multiple authentic sources, including the International Energy Agency, Carbon Capture and Storage Association (CCSA), Global CCS Institute reports and academic studies. Each source provides different types of data that contribute to a holistic understanding of technology performance. Key Performance Indicators (KPIs) such as CO_2 capture efficacy, cost per t of CO_2, energy requirements, lifetime emissions, and technological readiness are central to this process. Each KPI is analysed to assess its relevance and impact on the overall evaluation of the technology. The cost per t of CO_2 captured is a critical metric for determining economic feasibility, while energy requirements and lifetime emissions provide insights into the environmental impact of the technology. Data analysis involves a thorough examination of financial aspects, including capital expenditures (CapEx), operating expenses (OpEx), and potential income from carbon credits or carbon-based products. This financial analysis is essential for understanding the economic viability of each technology and its potential for large-scale deployment. Environmental data, including metrics on CO2 emission reduction and trade-offs, is also collected and analysed. This ensures that the environmental benefits of each technology are accurately assessed and that lifecycle emissions are considered. Data validation is performed to ensure accuracy and consistency, including cross-referencing with multiple sources and addressing any geographical or methodological biases. Standardization of data is crucial for ensuring comparability across different technologies. This involves normalizing data to control for variations in units, scales, and baseline assumptions. The analysis employs statistical and analytical techniques like scenario modelling, regression analysis, and sensitivity analysis, to derive meaningful conclusions about technology performance.

2.5 Application of Multi-Criteria Decision Analysis (MCDA)

The application of Multi-Criteria Decision Analysis (MCDA) is fundamental to the objective evaluation of carbon management systems. MCDA provides a structured approach to evaluating multiple criteria that may be conflicting, such as environmental impact, economic feasibility, and technological readiness. MCDA involves several key steps, starting with the identification of critical decision criteria. In the context of carbon management, these criteria typically include environmental sustainability, cost-effectiveness, and technological maturity. Each criterion is prioritized based on its importance, reflecting the strategic objectives of the organization and the preferences of stakeholders. The Analytic Hierarchy Process (AHP) is commonly used to determine the weights for each criterion. This process involves pairwise comparisons to assess the relative importance of each criterion, ensuring that the weights accurately represent their significance in the decision-making process. Once the criteria weights are established, each carbon management technology is evaluated based on these criteria. Performance ratings are assigned on a scale from 1 to 10, with higher scores indicating better performance. These ratings are derived from quantitative data, expert opinions, and performance assessments. The second phase of MCDA involves consolidating the scores using weighted sums. Each technology's score is calculated by multiplying its performance rating by the weight of each criterion. The aggregate of these weighted scores provides a cumulative performance grade for each technology. MCDA facilitates a transparent comparison of technologies, highlighting those that achieve the best balance between technological, economic, and environmental factors. This approach ensures that no single criterion dominates the decision-making process, leading to a more balanced and comprehensive evaluation.

2.6 Validation and Sensitivity Analysis

Validation involves checking the consistency and accuracy of data inputs and model outputs. This process includes comparing results with previous research, expert opinions, and empirical data to confirm that the assessment framework produces legitimate outcomes. The validation procedure often involves testing the framework with different datasets and scenarios to ensure that the results are consistent and repeatable. Sensitivity Analysis examines how variations in key assumptions or variables affect the results of the evaluation. This analysis helps identify which factors most influence technology rankings and scores. By systematically adjusting assessment criteria or technology ratings, sensitivity analysis uncovers the elements that have the greatest impact on the final evaluation outcomes. This analysis is essential for understanding the stability of the evaluation results under different conditions and assumptions. It ensures that the evaluation system is not biased by specific assumptions or inputs and that the rankings reflect the inherent performance of the technologies rather than the limitations of the evaluation framework. Validation and sensitivity analysis contribute to the overall credibility and reliability of the technology assessment, providing confidence that the selected technologies are evaluated fairly and accurately. These processes ensure that the evaluation framework is robust and capable of guiding effective decision-making in carbon management.

3. Results

TRL, CO_2 recovery costs per t, CO_2 collection efficacy, and lifecycle emissions are among the critical attributes of the dataset utilized to assess different carbon management strategies. The data utilized in this analysis, which factors for regional variations in technology efficacy and implementation, was sourced from a variety of sources, including academic research, industry publications, government databases, and pilot projects. We can confidently evaluate the technology in question with the abundance of data at our disposal.

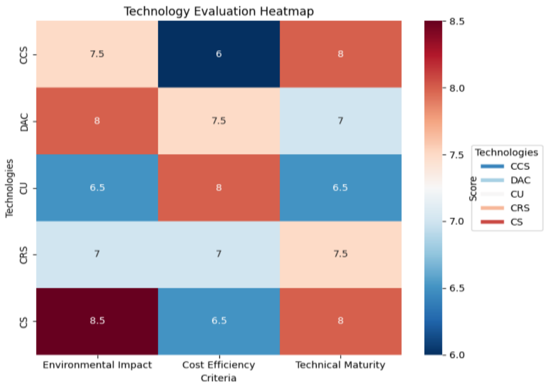

Figure 2: Performance of Carbon Management Technologies Across Criteria

Figure 2 illustrates the outcomes of an assessment of numerous carbon management systems according to three criteria: economic feasibility, technological maturity, and environmental impact. Where CCS stands for Carbon Capture and Storage, DAC for Direct Air Capture, CU for Carbon Utilization, CRS for Carbon Reduction Strategies, and CS for Carbon Sequestration.A critical component of any investigation is the utilization of validated and standardized data to evaluate the performance of a variety of technologies. The evaluation framework employs a weighted score system that considers three primary criteria: economic feasibility, technological maturity, and environmental impact. The economic feasibility of a project is evaluated by considering the cost of offsetting one metric t of CO_2, the potential revenue from carbon credits or products, and the total cost of ownership (TCO). Table 1 constitutes the results of the MCDA, all things considered. The environmental impact, economic feasibility, and technical maturity of each technology were taken into account to determine their ultimate weighted scores. With an aggregate score of 7.9, Carbon Reduction Strategies is the most effective strategy. As evidenced by their exceptional ratings, their concepts effectively integrate ecological consciousness, financial sustainability, and technological innovation. Consequently, Direct Air Capture (DAC) is ranked last with a weighted total score of 5.4. DAC's lower score suggests that there are challenges with fiscal viability and technological advancement, despite its potential as a CO_2 capture strategy.

Table 1: Multi-Criteria Decision Analysis (MCDA)

Technology	Environmental Impact Score	Economic Feasibility Score	Technical Maturity Score	Final Weighted Score
Carbon Capture and Storage (CCS)	3.2	1.5	2.1	6.8
Direct Air Capture (DAC)	2.8	1.2	1.5	5.4
Carbon Utilization	2.4	2.1	1.8	6.3
Carbon Reduction Strategies	3.6	1.8	2.4	7.9

The TRL scale measures technological maturity by measuring how far various technologies have come. Integrating these elements with a weighted scoring system allows for a full review of technology pros and cons.

Table 2: Comparison of existing and proposed method

Technology	Existing Method (Ju et al.)	Proposed Method
Carbon Capture and Storage (CCS)	3.2	1.5
Direct Air Capture (DAC)	2.8	1.2
Carbon Utilization	2.4	2.1
Carbon Reduction Strategies	3.6	1.8

Table 2 illustrates the superiority of the proposed evaluation framework over the existing system by conducting a comparison and contrast between the two. The existing methods focus on individual performance metrics, while the proposed method integrates a holistic evaluation model considering environmental, economic, and operational factors, providing a more comprehensive assessment of carbon capture technologies. The scope of analysis is occasionally limited by conventional methods, which concentrate on discrete metrics, such as cost or environmental impact. In Figure 3, the metrics utilized by existing methodologies are contrasted with those of the proposed framework, illustrating the latter's more evaluation perspective.

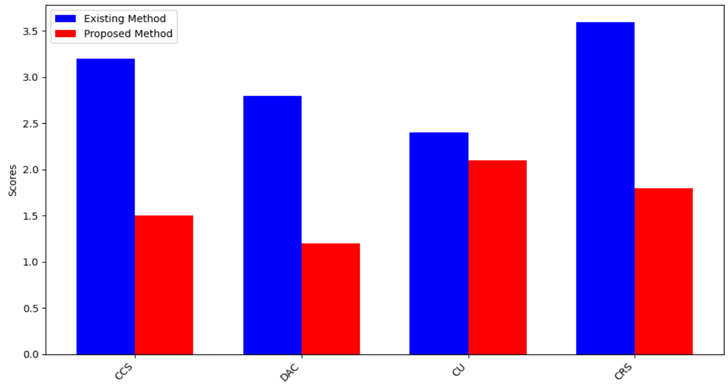

Figure 3: Comparison of Proposed Method with Existing System

The detailed analysis emphasizes the importance of a comprehensive strategy that incorporates a variety of technologies to effectively address the diverse needs and circumstances. CCS is highly effective in reducing environmental impact; however, the technology may not be suitable for widespread use until costs continue to decrease. In contrast, carbon utilization technologies have superior economic feasibility scores, which presents a practical and cost-effective alternative for carbon management. The proposed evaluation method offers a more thorough and sophisticated analysis of carbon management strategies. The incorporation of a variety of factors enables a more comprehensive comprehension of the benefits and drawbacks of each technology, thereby facilitating the achievement of long-term environmental objectives and the effective mitigation of climate change. As a result, this results in improved decision-making capabilities.

4. Conclusion

This study evaluates various carbon management technologies, focusing on economic, environmental, and technological aspects. The technological analysis encompasses methods for reducing emissions, utilizing captured carbon, storing it, and direct air capture. In order to identify the most successful, cost-effective, and energy-efficient technologies, the study implemented Multi-Criteria Decision Analysis (MCDA). Based on the data, both DAC and CCS are equally effective in significantly reducing CO_2 emissions. CCS has a cost efficacy of $50 to $150 per t, whereas DAC has a range of $100 to $500 per t of CO_2 captured. In the long term, carbon utilization technology more than recoups its initial costs through product sales and carbon credits, despite the potential for higher initial expenditures. The results indicate that the successful attainment of various carbon management objectives necessitates the integration of utilization technology, DAC, and CCS to varying degrees. It is permissible to refrain from relying on a single technology; rather, solutions should be customized to accommodate each unique circumstance. Businesses and organizations have collaborated to reduce their environmental impact and energy consumption by utilizing sustainable products that are composed of biodegradable and recyclable materials. These partnerships have resulted in the integration of contemporary conveniences into the daily lives of all individuals. The implementation of a multifaceted strategy that capitalizes on business partnerships can result in substantial progress in the areas of carbon management, climate change mitigation, and the achievement of long-term environmental objectives.

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