Decarbonization through Carbon Capture and Storage Applications for Saudi Arabia

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Abstract-* Carbon capture and storage (CCS) is recognized as a promising approach for reducing greenhouse gas emissions while ensuring industrial and energy production. The present study aims to review literature on the application of CCS technologies in Saudi Arabia because of its significance for the national economy. The analysis focuses on carbon capture methods, associated technologies, and storage potential as well as case studies and projects on enhanced oil recovery, low-carbon hydrogen production, and CCS. The findings indicate that Saudi Arabia has considerable potential for adopting and implementing CCS technologies due to the availability of geological storage, energy infrastructure, and supportive initiatives undertaken by authorities. At the same time, the high costs of capture, energy intensity, regulatory risks, and operational barriers hinder the country's capacity to scale up CCS use. The study concludes that the Saudi government needs to prioritize investments in carbon capture and storage infrastructure to ensure the country's transition to net-zero emissions and promote sustainable economic growth while supporting the energy sector's transformation into a low-carbon industry.

***Keywords* - Carbon Capture and Storage, Decarbonization, Saudi Arabia, Carbon Emissions, Saudi Vision 2030, Carbon Neutrality, Climate Change.**

I. INTRODUCTION

Greenhouse gas (GHG) emissions from human activities are intensifying climate change worldwide, causing environmental disruptions, rises in ocean levels, extreme weather, and other ecological hazards. Carbon dioxide (CO2) is the largest single component of GHGs emanating from human activities, representing three-quarters of all greenhouse gas emissions, primarily generated by burning fossil fuels, industrial processes, and electricity production (IPCC 2023). Therefore, the need to reduce carbon emissions is becoming even more critical for countries to meet the goals of the Paris Agreement while limiting temperature rise to one and a half or two degrees Celsius (IEA 2024). Notably, Saudi Arabia is among the leading oil producers and exporters, a country whose economy has been overly dependent on hydrocarbon production, thus creating complex challenges in the transition to a low-carbon economy. This country cannot achieve its economic development goals while also cutting carbon emissions from oil processing, petrochemicals, cement, steel manufacturing, and power plants (Al Shehri et al. 2023). However, Saudi Arabia is also among the nations that have pledged to make significant efforts to promote sustainability and curb greenhouse gas emissions, as demonstrated by the Saudi Green Initiative and Vision 2030 (Saudi Green Initiative 2023). Thus, this paper discusses the role of Carbon Capture and Storage (CCS) in decarbonization and carbon management, with a focus on opportunities and challenges in Saudi Arabia.

1.1 Decarbonization and the Need for Carbon Capture and Storage

Decarbonization entails a shift from a carbon-based economy to a zero-carbon economy while ensuring that economic activities, particularly the industrial sector, continue to operate. Although there has been significant progress in the growth of renewable energy, some industrial activities are energy-intensive and may not be ready to adopt the existing alternatives, requiring new methods and technologies to abate carbon emissions. For instance, the production processes in cement, steel, fertilizer, chemical manufacturing, and petroleum refining are energy-intensive and result in substantial emissions, even when alternative energy is used (IEA 2024). Carbon Capture and Storage is a proven technology that can help in minimizing and controlling carbon emissions from major industrial sources while enabling the transformation to a net-zero or low-carbon economy. According to Global CCS Institute (2024), CCS refers to the capturing and storage of all possible CO2 emissions from industrial facilities and power plants, with the gas being transported through pipelines or other mechanisms to suitable underground storage sites. CCS provides a credible solution for reducing carbon emissions from major emitting sectors while allowing these facilities to continue operating profitably while contributing to efforts aimed at combating climate change. Additionally, recent advancements in capture technologies and the utilization of captured emissions for cleaner energy production offer new opportunities to scale up CCS and adopt it as a strategic option for decarbonization.

1.2 Carbon Capture and Storage in Saudi Arabia

Saudi Arabia has the potential to lead the way in the Middle East and the world in adopting CCS technology and capitalizing on the opportunities it presents in the fight against climate change while at the same time deriving economic benefits from its adoption. First, the kingdom has vast carbon storage sites and reservoirs suitable for long-term storage of CO2 captured from industrial facilities and power plants. At the same time, Saudi Arabia has the technical expertise, capital, and existing oil and gas infrastructures that could be leveraged to build carbon capture and storage facilities (Amin et al. 2022). Moreover, the Saudi government has demonstrated its commitment to capturing carbon emissions by supporting various CCS initiatives and engaging both local and international partnerships to implement projects, ensure enhanced oil recovery, and produce clean energy, including blue hydrogen from captured emissions (IEA 2024). These efforts align with the goals of the Circular Carbon Economy (CCE), a G20 initiative that encourages countries to participate in reducing, reusing, recycling, and removing carbon emissions as a way of adapting carbon management policies that enhance their climate change adaptation and mitigation capabilities (G20 CCE Platform 2022).

1.3 Challenges and Opportunities

Although Saudi Arabia has made efforts to capitalize on the potential of CCS, several challenges hinder its adoption and efficient implementation in the country. For instance, carbon capture technologies are capital-intensive and energy-intensive, thus raising concerns about the additional costs that may be incurred by emission-intensive industries that decide to adopt them, such as petrochemicals, cement, and fertilizers (Haszeldine & Scott 2021). Additionally, the development of associated infrastructure, including transport networks for conveying captured emissions to storage sites, poses significant technical, economic, and regulatory challenges. Besides these technical and regulatory barriers, there are environmental and social concerns surrounding CCS, including the safety of geologic storage and public perception of the technology (Haszeldine & Scott 2021). Thus, the adoption of carbon capture and storage technologies in Saudi Arabia requires addressing the technical, regulatory, and financial constraints associated with it. On the other hand, overcoming these challenges will create opportunities for the country to benefit from CCS's economic and climate advantages. For instance, apart from reducing carbon emissions and meeting international obligations regarding climate change, carbon capture and storage open the door for enhanced oil recovery, production of cleaner energy, attracting new investment opportunities in the clean energy sector, and creating employment opportunities in the process.

II. LITERATURE REVIEW

2.1 Overview of Carbon Capture and Storage (CCS)

It is well established that Carbon Capture and Storage (CCS) represents one of the most promising ways for lowering carbon dioxide (CO2) emissions from major anthropogenic industrial sources. This technology encompasses the separation of CO2 from large point sources, as well as the transportation and long-term sequestration of the gas in underground geologic formations. Thus, CCS is considered essential for reducing emissions from carbon-intensive industrial sectors that are challenging to decarbonize, according to the International Energy Agency (IEA, 2024). These industries include cement, steel, petrochemicals, and power, among others. In addition, recent innovations in CCS make it an attractive option for long-term emission reduction (Global CCS Institute, 2024).

Table 2.1. Comparison of Major Carbon Capture Technologies

Carbon Capture Technology	Principle	Advantages	Limitations
Post-combustion Capture	CO_2 is removed from flue gases after fuel combustion	Can be retrofitted to existing plants	High energy consumption
Pre-combustion Capture	Carbon is removed before combustion through gasification	High capture efficiency	High installation cost
Oxy-fuel Combustion	Fuel is burned in pure oxygen to produce concentrated CO_2	Produces high-purity CO_2	Requires oxygen production unit

Research indicates that post-combustion capture is the most widespread technique as it can be retrofit in existing facilities with a minimal number of infrastructure changes, while the other two options are more appropriate for new power plants (Boot-Handford et al., 2019).

2.2. Carbon Capture and Storage Applications in Saudi Arabia

This figure illustrates how carbon capture and storage (CCS) supports emissions reduction efforts in Saudi Arabia by capturing CO_2 from hydrocarbon-based activities and enabling long-term carbon management solutions aligned with national sustainability goals.

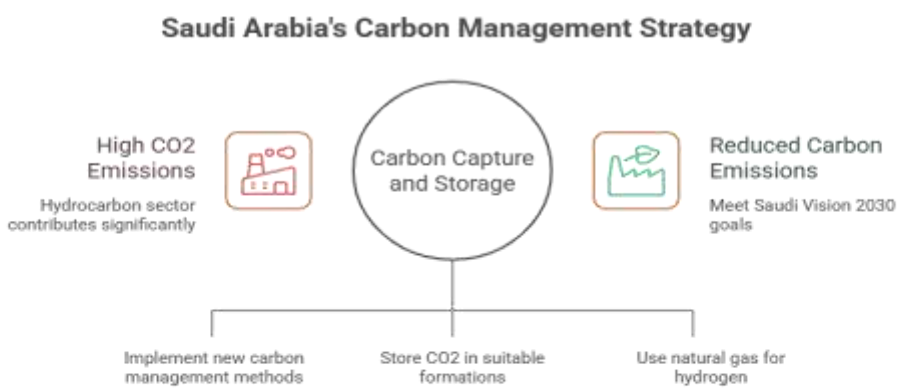

Figure 1. The Role of Carbon Capture and Storage in Saudi Arabia's Carbon Management Strategy

The need for carbon capture and storage (CCS) has become a strategic priority for the country due to the significant contribution of CO2 emissions from the hydrocarbon sector to the atmosphere. Therefore, Saudi Arabia aims to reduce carbon emissions and meet the goals of Saudi Vision 2030 and the Saudi Green Initiative by developing and adopting novel technologies for carbon management. According to Amin et al. (2022), the country has appropriate geological formations for long-term CO2 sequestration and natural gas resources for hydrogen production. This potential for the creation of a hydrogen economy in the kingdom is based on the availability of depleted gas fields and saline aquifers suitable for carbon storage, and the developed gas production infrastructure for capturing and transporting CO2.

Moreover, several carbon capture and storage projects have already been initiated and are considered viable for their potential to transform the energy market by developing and demonstrating carbon technologies and their integration with enhanced oil recovery and blue hydrogen production

(Global CCS Institute, 2024). This implies that Saudi Arabia plays a leading role in the Middle East region in reducing greenhouse gas emissions through carbon capture and storage activities.

Table 2.2. Reported Benefits of CCS Deployment in Saudi Arabia

Application Area	Expected Benefit
Power Generation	Reduction of CO_2 emissions from fossil-fuel plants
Oil and Gas Industry	Enhanced Oil Recovery (EOR) and emission reduction
Hydrogen Production	Supports low-carbon (blue) hydrogen production
Industrial Manufacturing	Lower emissions from cement, steel, and petrochemical industries
Climate Policy	Supports Saudi Vision 2030 and net-zero ambitions

2.3 Research Gaps

While significant research has been conducted on various aspects of the carbon capture and storage (CCS) methods used in Saudi Arabia, most of it concentrates on the technical aspects, and leaves economic and policy-related issues, as well as storage monitoring and management, understudied (IEA, 2024). Additionally, the implications of combining CCS with other low-carbon technologies, such as hydrogen production and the development of a circular carbon economy, require further investigation. Addressing these gaps in research will contribute to developing a comprehensive understanding of CCS's role in achieving Saudi's carbon reduction goals and advancing policy design in the future.

III. METHODOLOGY

The present study employed a systematic literature review (SLR) methodology to identify the role of Carbon Capture and Storage (CCS) in decarbonization in Saudi Arabia. A systematic review was selected because it allows retrieving, evaluating, and synthesizing research evidence with minimal biases while increasing reliability (Page et al., 2021). In particular, this study's research question required exploring up-to-date topics related to decarbonization, including Carbon Capture and Storage (CCS), its implementation in various sectors, and Saudi Arabia's response to CCS-related requirements.

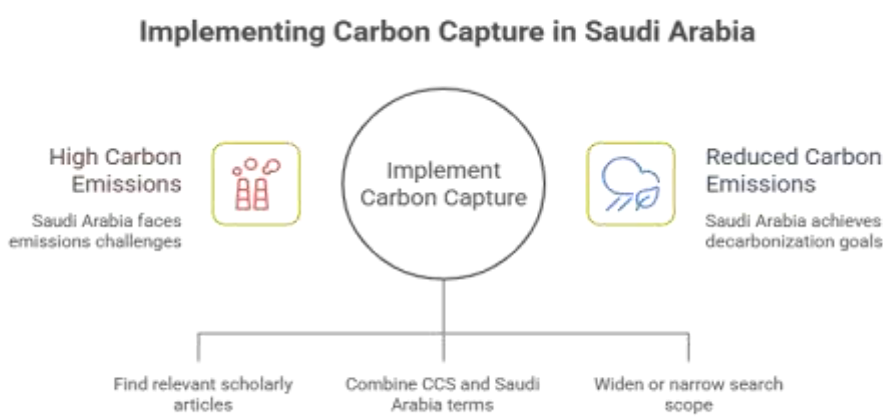

Figure 2. Carbon Capture Implementation Pathways for Emissions Reduction in Saudi Arabia

This figure illustrates the implementation of carbon capture technologies as a strategy for reducing carbon emissions in Saudi Arabia. The framework highlights the transition from high carbon emissions to decarbonization outcomes through the deployment of carbon capture solutions that support national climate and sustainability objectives.

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Several databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, IEEE Xplore, and Google Scholar, were leveraged to find relevant scholarly articles published in professional journals and books. The search strategy combined keywords related to "Carbon Capture and Storage" (CCS), "Saudi Arabia," "decarbonization," "carbon emissions," "CCS implementation," "geological storage," "enhanced oil recovery," and "Saudi Vision 2030." Particular search strings included "CCS Saudi Arabia," "Carbon capture and storage in Saudi Arabia," "CCS and decarbonization," "CCS and emissions in Saudi Arabia," "Geological storage in Saudi Arabia," "Enhanced oil recovery and CCS," "CCS and Saudi Vision 2030," etc. Additionally, Boolean operators (AND, OR) were applied to widen or narrow the search scope (Kitchenham & Charters, 2007).

Prior to inclusion in the final list of studies, each article underwent the screening process to ensure that all sources met the inclusion criteria and there were no redundant, irrelevant, or duplicative resources. In particular, the following requirements had to be met: a scholarly article, published in a refereed journal or conference, written in English, published between 2020-2026, and addressed Carbon Capture and Storage (CCS) in Saudi Arabia explicitly or implicitly. On the other hand, articles published before 2020, non-English, non-scholarly, or unrelated to the chosen topic (e.g., no CCS) were excluded from consideration.

Table 3.1. Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Publication Period	2020–2026	Before 2020
Language	English	Non-English publications
Document Type	Peer-reviewed journals, conference papers, and official reports	Editorials, news articles, unpublished manuscripts
Study Focus	CCS technologies, decarbonization, Saudi Arabia, carbon management	Studies unrelated to CCS or Saudi Arabia

The initial step after the screening process of eligible works involved conducting the qualitative synthesis process. The included information from the articles identified during the screening process was examined, extracted, evaluated, and organized into themes by considering the information on CCS technology, storage methods, policies, costs, industrial uses, and challenges. The information helped highlight trends, gaps, and opportunities for CCS in Saudi Arabia and its role in achieving carbon neutrality in the country (Snyder, 2019).

IV. RESULTS

The systematic review highlighted that Carbon Capture and Storage (CCS) is among the most promising technologies that can help achieve Saudi Arabia's goal of promoting oil and gas production while decarbonizing the nation's economy. The analyzed articles revealed that CCS could make a significant difference in reducing CO2 emissions from large industrial sources like power plants, petroleum refineries, petrochemicals, cement, and hydrogen production. Moreover, most of the studies found that geological storage potential and existing petroleum infrastructure present great opportunities for Saudi Arabia to scale up CCS to commercial levels (IEA, 2024; Global CCS Institute, 2024).

4.1 Distribution of the reviewed studies

The reviewed studies identified five themes with a substantial number of related articles, including carbon capture and storage technologies, geological storage potential, industrial applications, economic and policy aspects, and implementation barriers. Notably, the first two themes garnered the highest research attention and investment in terms of manpower and resources due to their significance in ensuring effective CCS technology and securing storage sites.

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Table 4.1. Summary of Major Findings from the Reviewed Literature

Research Area	Key Findings	Overall Observation
CCS Technologies	Post-combustion capture is the most widely adopted technology due to easier integration with existing facilities.	High technological maturity
Geological Storage	Deep saline aquifers and depleted oil reservoirs provide substantial CO_2 storage capacity.	Strong storage potential
Industrial Applications	CCS is widely applicable in power plants, refineries, petrochemical industries, and blue hydrogen production.	Broad industrial adoption
Policy Framework	Saudi Vision 2030 and the Saudi Green Initiative encourage investment in carbon reduction technologies.	Positive policy support
Implementation Challenges	High capital cost and energy consumption remain major barriers.	Requires further investment

The reviewed studies indicate that post-combustion capture remains the preferred technology because it can be retrofitted into existing industrial plants with relatively lower infrastructure modifications compared to pre-combustion and oxy-fuel systems (Global CCS Institute, 2024).

4.2 CCS Applications in Saudi Arabia

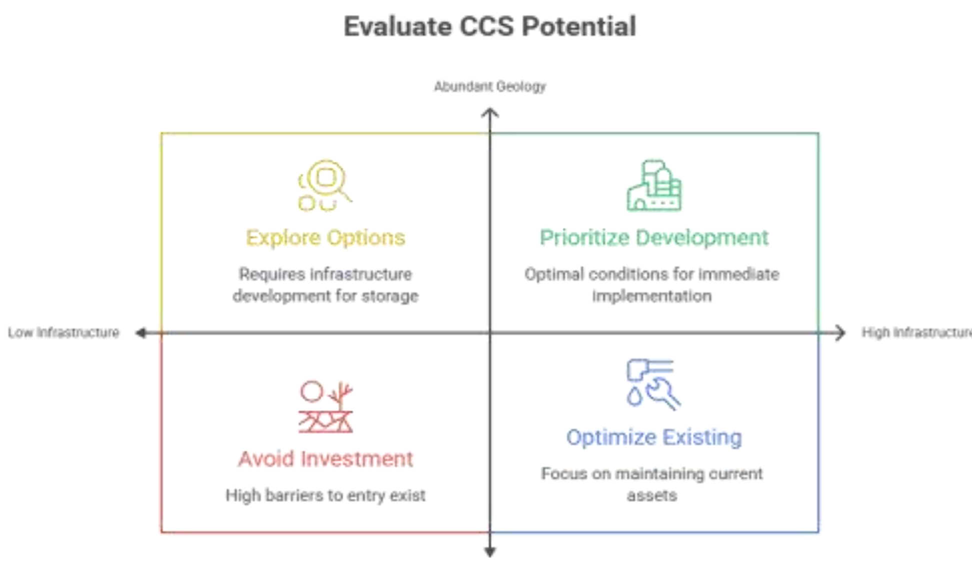

Figure 3. Strategic Framework for Evaluating Carbon Capture and Storage (CCS) Potential

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This figure illustrates a decision-making matrix for evaluating carbon capture and storage (CCS) opportunities based on geological suitability and infrastructure availability. The framework categorizes potential CCS investments into four strategic pathways: prioritizing development, optimizing existing assets, exploring future opportunities, or avoiding investment, thereby supporting effective resource allocation and deployment planning.

Based on the reviewed studies, Saudi Arabia has several advantages for large-scale carbon capture and storage (CCS) implementation. First, the country has significant oil and gas production infrastructure that can be repurposed for transporting and storing carbon dioxide (CO2), thus, reducing costs associated with CCS (Amin et al., 2022). Second, Saudi Arabia can benefit from its geology, which provides multiple storage options for captured carbon, including depleted oil and gas reservoirs and deep saline aquifers (Global CCS Institute, 2024). These factors make the Kingdom one of the most promising countries in the Middle East for future CCS development.

The reviewed literature also indicates that there are various applications of CCS in different economic sectors in Saudi Arabia. For instance, in the power sector, CCS can be used to capture carbon emissions from fossil fuel power plants, thus, reducing greenhouse gas emissions from the electricity generation industry while ensuring continuous electricity supply (IEA, 2024). In the oil and gas sector, CO2 can be injected into oil reservoirs to increase production through enhanced oil recovery while sequestering the gas underground (Haszeldine & Scott, 2021). The petrochemical and cement industries can also benefit from CCS adoption because it can help reduce hard-to-abate emissions, which are challenging to eliminate using renewable energy sources (Haszeldine & Scott, 2021). Another promising application of CCS in Saudi Arabia is the production of blue hydrogen through carbon capture from natural gas (IEA, 2024). This will enable the country to participate in the growing hydrogen economy while reducing carbon emissions using its abundant natural gas resources. Overall, the reviewed studies indicate that CCS has multiple applications in various economic sectors while supporting Saudi Arabia's decarbonization goals.

4.3 Challenges Affecting CCS Deployment

Despite the potential of CCS to mitigate carbon emissions, the reviewed literature indicates that several challenges hinder its large-scale deployment in Saudi Arabia. The most common challenge reported in the reviewed articles is the high capital costs of building and operating carbon capture and storage facilities, which reduces the economic viability of CCS (Amin et al., 2022). Another challenge is the lack of government incentives for private organizations to invest in CCS technology (Haszeldine & Scott, 2021). Moreover, the reviewed studies report the technical challenges associated with transporting and storing CO2, which requires specialized infrastructure (Amin et al., 2022). These factors contribute to the high costs of CCS, limiting its adoption in Saudi Arabia.

On the other hand, some studies highlight the potential of CCS to support Saudi Arabia's transition to a net-zero economy while promoting economic growth through investment in new technology (IEA, 2024). For instance, CCS can reduce carbon emissions from hard-to-abate sectors, including power, petrochemicals, and cement, thus, supporting the Kingdom's carbon neutrality goals. Additionally, the technology can be used to manufacture blue hydrogen, which is in high demand globally, therefore, creating economic opportunities for the country. Overall, the reviewed literature indicates that while there are potential challenges affecting large-scale CCS deployment in Saudi Arabia, the country stands to benefit significantly from its strategic application in the economy.

4.4 Summary of Results

Based on the results of the review, one can conclude that Carbon Capture and Storage can be a strategically viable option for decarbonizing Saudi Arabia. The country possesses ample geological storage sites, a robust petroleum-based economy, and unwavering support from the government via Saudi Vision 2030 and the Saudi Green Initiative (Saudi Green Initiative, 2023). Indeed, the reviewed articles confirm the feasibility of applying CCS to reduce carbon emissions from power plants, petroleum refineries, petrochemical complexes, cement factories, and hydrogen production facilities while ensuring continued economic prosperity and energy security.

Nevertheless, the review also revealed that achieving the desired impact on a larger scale will require addressing a set of impediments, including extremely high costs, energy intensity, transport infrastructure, regulatory framework, and storage monitoring and verification (IEA, 2024). It is evident that CCS's role in helping Saudi Arabia become a carbon-neutral country and achieve its climate goals will be determined by its innovators' ability to promote continuous technology development, supportive policies, and economic incentives.

V. DISCUSSION

The findings of this study indicate that carbon capture and storage (CCS) is a vital and integral measure with which Saudi Arabia can transition into a low-carbon economy while still supplying the world with its energy resources. The review has shown that compared to other methods, CCS is an innovation that directly targets hard-to-abate sectors and reduces carbon emissions from oil and gas, petrochemical, cement, and steel production to a considerable extent (IEA, 2024). These industries are of utmost importance to the national economy; therefore, investing in their decarbonization is necessary for any country with similar economic interests.

According to the findings, the Kingdom has distinct advantages over other countries in terms of CCS implementation because of the country's natural resources and already existing gas infrastructure that can be used for storage. This study's findings corroborate with those of the Global CCS Institute (2024), which state that Saudi Arabia has considerable potential for carbon storage due to its natural gas resources. The report also adds that the country has the necessary infrastructure to facilitate large-scale CCS.

Another significant finding of this review is that carbon capture can be combined with enhanced oil recovery and blue hydrogen production to make additional profit from byproducts while also reducing atmospheric carbon levels. For instance, the utilization of CO 2 for enhanced oil recovery (EOR) practices can create an additional source of revenue for energy companies while facilitating oil production and reducing greenhouse gas emissions. Similarly, CCS can be applied during hydrogen production to create blue hydrogen and supply the market with another clean energy source while contributing to the decarbonization of oil production (Amin et al., 2022). These capabilities make CCS a particularly attractive technological innovation that can reshape the energy sector's future for the better while also providing significant economic benefits to energy companies.

The findings of this study also outline some of the major concerns related to CCS, including the high costs of equipment needed to facilitate carbon capture, as well as the substantial amount of energy that is required to operate these machines. The expenditure on energy can become prohibitively expensive if carbon capture plants are not built next to renewable energy sources; thus, CCS can lead to the creation of new emission sources if carbon capture plants are not properly maintained (IEA, 2024). This limitation can be overcome by ensuring that carbon capture facilities use clean energy sources. Nevertheless, it is evident that significant investment will be required to make these technologies viable and profitable on a large scale.

Another limitation highlighted by the findings is that carbon capture and storage require appropriate regulatory and policy frameworks to ensure their safe and reliable operation. The review found that many previous studies stress the importance of appropriate legislation that will facilitate the operation of CCS while also ensuring safety and community support. For instance, Haszeldine & Scott (2021) note that regulatory and policy frameworks are key factors in determining the success of any carbon storage endeavor. Therefore, it is necessary for the government to take proactive measures to establish the necessary legal, regulatory, and policy initiatives while also building domestic expertise in the field to ensure that all operations run smoothly and without unnecessary risks.

The findings of this study indicate that carbon capture and storage should be viewed as a major initiative for Saudi Arabia to shift towards a low-carbon future while also meeting its national economic goals. According to the findings, CCS has tremendous potential, but it must be supported by policy and legislative measures to ensure its viability and long-term success. Additionally, this review has found that CCS can be utilized together with renewable energy sources and other clean technologies, such as blue hydrogen production, to create an integrated sustainable development concept known as a circular carbon economy (Saudi Green Initiative, 2023).

VI. CONCLUSION

Review of the selected readings suggests that Carbon Capture and Storage (CCS) is a strategic technology for reducing greenhouse gas emissions while still allowing industrialization and economic development in the Kingdom. The article highlights the status of CCS in Saudi Arabia, which includes technological considerations, geological storage options, industrial applications, policy developments, and potential challenges associated with its implementation. From the review, it is evident that the Kingdom has great potential based on its storage resources, existing oil and gas infrastructure, and Saudi vision 2030 and Saudi Green Initiative (Saudi Green Initiative, 2023). The findings also confirm that CCS can make a significant contribution to reducing carbon emissions from major sources in the country such as the power sector, petroleum, petrochemicals, cement, and hydrogen production. Additionally, the integration of CCS with enhanced oil recovery and blue hydrogen production will enhance profits from oil production and achieve the country's decarbonization goals (Amin et al., 2022). Such benefits make CCS a key technology for Saudi Arabia and the whole region in the years to come.

However, even though CCS has the potential to play a critical role in future energy and industrial sectors in the Kingdom, its deployment faces several challenges and barriers like high costs, carbon capture intensity, regulatory risks, and the need for transportation and storage infrastructure (IEA, 2024). In this context, it is worth noting that the successful commercialization and deployment of this technology require sustained efforts, including continued R&D, supportive government policies, investment attraction, and collaboration between firms and policymakers.

Based on the discussions, it is evident that CCS will be a critical player in decarbonizing Saudi Arabia's energy system and supporting its carbon neutrality targets. Besides adopting renewables and energy-efficient technologies and investing in low-carbon hydrogen production, the country needs CCS to meet its economic development and energy security needs while reducing greenhouse gas emissions. Therefore, future studies should emphasize the optimization methods and strategies to reduce costs, promote regulatory frameworks, and assess the sustainability of storage sites to maximize the benefits of deploying CCS technology in the Kingdom (Global CCS Institute, 2024).

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