SGI-JOURNAL OF SCIENCE AND TECHNOLOGY

VOLUME. 10
ISSUE. 1
FEB., 2026

CARBON CAPTURE AND STORAGE (CCS) IN PETROLEUM OPERATIONS: TECHNO-ECONOMIC VIABILITY, POLICY ARCHITECTURE, AND REGULATORY READINESS FOR A NET-ZERO TRANSITION

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Abstract
The increasing pressure from climate governance and net-zero commitments means Carbon Capture and Storage (CCS) is becoming a key decarbonization pathway for petroleum operations This research looks at the techno-economic viability, regulatory readiness and policy coherence of CCS deployment in petroleum value chains, specifically the upstream and midstream. This study is using mixed-method approaches which combine with a secondary techno-economic data, policy and regulatory document analysis as well as comparative synthesis of global CCS deployment experience to evaluate capture technologies, storage option, transport economics and governance. This evaluation will shape the investment decision making of CCS through a detailed assessment of the identified element and associated risks. Research shows that capture and storage technologies have achieved a high level of technical maturity, yet their economic viability remains highly sensitive to carbon prices, fiscal support, availability of infrastructures and regulatory certainty. CCS deployment readiness is significantly higher in jurisdictions with integrated policy frameworks, clear liability rules and supporting market instruments. In contrast, large-scale deployment is still impeded by regulatory fragmentation, public acceptance issues and uncertainty on long-term monitoring responsibilities. The conclusion of the study is that CCS can play a transitional but critical role in petroleum-dependent economies provided that they are embedded within coherent energy transition strategies. Moreover, there must be robust governance mechanisms in place for it to work. Policy recommendations highlight the importance of stable carbon markets, on-target fiscal incentives, one set of regulatory standards, and CCS in energy and climate policies. This work on CCS readiness offers a techno economic synthesis from a governance-centered perspective. This imparts insights on the relevance of institutional determinants for scalability in fossil-fuel-based energy systems.
Keywords: Carbon Capture and Storage, Petroleum Economics, Energy Policy and Governance, Decarbonization, Net-Zero Transition.

I. Introduction

The oil sector is indispensable for energy, industry, and government in many resource-dependent countries, helping to drive economic growth. Oil and gas operators undertake one of the largest industrial deployments of technology to deliver energy that meets the requirements of the low carbon transition (Haszeldine et al. 2018, Holz 2021), while at the same time being amongst the largest anthropogenic emitters of CO_2. The deployment of renewable energy and energy efficiency improvements are critical for decarbonisation in the long term, however, Carbon Capture and Storage (CCS) has become an important approach for delivering large emissions cuts in existing oil infrastructures (Aminu et al., 2017; Gür, 2022).

Carbon capture and storage (CCS) takes the form of capturing CO_2 at large point sources, transporting it by pipeline or shipping, and long-term storage in geological formations such as depleted oil and gas reservoirs, and saline aquifers (Ajayi et al., 2019; Ali et al., 2022) CCS offers significant opportunities for petroleum operations. Specifically, CCS can facilitate the emissions abatement from gas processing, refineries, and EOR systems. Furthermore, oil and gas companies have the subsurface skills and infrastructure (Barbera et al, 2022; Bashir et al, 2024a) to implement such strategies. Even though CCS technology has a lot of potential, it has not been deployed evenly across regions due to high capital costs, uncertain revenues, regulatory uncertainty, and public acceptance challenges (Braun, 2017; Hong, 2022a).

From the perspective of petroleum economics and policy, CCS adoption is a governance-driven investment choice rather than a technological one; it is shaped by carbon pricing mechanisms, fiscal incentives, liability regimes and institutional capacity (Fuss et al., 2018; Galeazzi et al., 2023). The lack of clear regulatory frameworks and long-term policy commitment continues to erode private sector confidence in developing and fossil-fuel-dependent economies. Unsurprisingly, understanding CCS readiness requires a thorough assessment of its techno-economic performance together with policy and regulatory conditions.

Against this backdrop, this study pursues two core objectives:

To evaluate the techno-economic viability of CCS deployment in petroleum operations across the capture, transport, and storage value chain; and

To assess the adequacy of existing policy and regulatory frameworks in enabling scalable and economically sustainable CCS implementation within petroleum-based energy systems.

II. Conceptual and Theoretical Framework

This section situates CCS within a structured conceptual and theoretical lens, linking petroleum economics, policy, and governance considerations to the technical and financial realities of CCS deployment.

Carbon Capture and Storage (CCS) Technology

According to Gür (2022) and Ajayi et al. (2019), CCS is the process of capture, transport and storage of CO_2. Capture technologies may be characterised as post-combustion, pre-combustion, and oxy-fuel combustion. Each technology possesses different energy requirements, capture efficiencies and cost profiles (Al Mesfer et al. 2024; Heldebrant et al. 2022). According to Hamdy et al. (2021), post-combustion capture through the use of amine-type solvent is the most applicable technology for retrofitting an existing petroleum facility. Lee and Park (2015) indicate that pre-combustion capture is applicable for new integrated gasification combined cycle (IGCC) plants. Storage uses geological reservoirs like depleted oil and gas fields and deep saline aquifers for permanent disposition of carbon dioxide and enhanced oil recovery (Ali et al., 2022; Bashir et al., 2024a). It is vital to understand these technological pathways in order to evaluate their efficiency, scalability, and operational use in petroleum operations.

Techno-Economic Viability and Policy Readiness

The capital and operational expenditures, carbon price, and policies can affect the CCS (carbon capture and storage) economic viability (Barbera et al., 2022; Hong, 2022a). Pricing carbon amid transport, power, and industrial use reduces social cost by establishing a carbon price to promote carbon capture use and sequestration (WMO, 2021). It provides funding to lessen CCS cost. The clarity of regulations, allocation of liability, standards for monitoring, and permitting processes all fall under policy readiness and help lower investment risk and increase uptake (Braun, 2017; Galeazzi et al., 2023). A holistic understanding of the adoption potential of CCS in petroleum-dependent economies can be achieved by combining techno-economic assessment with policy evaluation.

Theoretical Foundation: Technology-Policy Integration Model

The study draws on a TPI framework positing that large-scale deployment of industrial technology, such as CCS, depends on the interplay between technical performance, commercial viability, and governance (Haszeldine et al., 2018; Hong, 2022a). The TPI framework highlights that technology alone is not sufficient for deployment. It must also be supported by regulatory frameworks, market instruments, and institutional capacity to manage risks and align private incentives with the climate objectives of society. The TPI framework, used in petroleum operations, considers carbon capture storage (CCS) in terms of engineering, economics and policy. It concentrates on engineering criteria such as capture efficiency and storage integrity, economic criteria such as CAPEX, OPEX and carbon pricing, and policy instruments such as regulations, subsidies, permitting. It provides a systematic approach to evaluate readiness and identify barriers.

III. Literature Review

This literature review synthesizes scholarly insights on CCS in petroleum operations, integrating techno-economic, policy, and governance perspectives. The review is structured into five thematic areas, highlighting advances, contrasts, and gaps.

CCS Capture Technologies

The most scholarly investigations into carbon capture, use and storage (CCS) have been of the three types of capture technology: post-combustion, pre-combustion and oxy-fuel (Al Mesfer et al., 2024; Hamdy et al., 2021) . The amine-based solvent post-combustion capture became the most widespread approach in retrofitted petroleum plants due to moderate capital requirement and high flexibility (Lee & Park, 2015; Heldebrant et al., 2022). More thermodynamically efficient, pre-combustion capture requires integrated gasification systems making it less amenable to retrofitting (Hong 2022a) Oxy-fuel combustion provides highly pure CO_2 but also imposes further energy penalties and oxygen supply costs (Barbera et al., 2022). According to various studies, selection of the capture technology relies upon the type of facility, integration in energy system, and economic situation. This indicates techno-economic optimization for planning in petroleum operations (Gür, 2022; Ajayi et al., 2019).

CO_2 Transport and Storage Mechanisms

The scalability of CCS is influenced by the transport and storage of CO_2. The most economical means of transport for large and continuous streams of CO_2 is pipeline networks, while shipping is being considered for sources dispersed geographically (Michaelides, 2021; Galeazzi et al., 2023). The use of depleted oil and gas reservoirs for storage serves two purposes: a permanent place of sequestering and enhanced oil recovery (Ali et al., 2022; Bashir et al., 2024a).

Saline aquifers have large storage potential, but require a lot of monitoring and models to mitigate leakage (Ajayi et al., 2019). Studies have shown that while the selection of a storage site, injectivity and geomechanical integrity are key determinants of long-term effectiveness, regulatory frameworks often fail to provide definitions of monitoring and liability obligations (Braun, 2017; Hong, 2022a).

Economic Feasibility and Cost Analysis

According to techno-economic analyses, the adoption of CCS is highly sensitive to CAPEX, OPEX, and carbon pricing (Barbera et al., 2022; Hong, 2022a). According to estimates from Fuss et al. (2018), petroleum facilities with post-combustion capture could see operational cost increases of 30–60% requiring funding. Research in developed countries indicates that a strong carbon market, along with tax credits and subsidies, substantially enhance the investment case (Holz et al., 2021; Galeazzi et al., 2023). On the other hand, fragmented policy frameworks in developing economies are leading to increased cost uncertainty and investment risk, which limits the scale up of CCS. Interminded economic feasibility, policy readiness and governance stability seem possibility, according to the findings.

Policy, Governance, and Regulatory Readiness

Governance has a key role in CCS adoption. The private sectors participation is highly impacted by regulatory clarity on permitting, liability allocation, monitoring and long-term stewardship (Braun, 2017; Galeazzi et al., 2023). According to the study by Haszeldine et al., an integrated approach allows for better deployment of Carbon Capture and Storage (CCS).

Although technical studies often overlook public acceptance, it too is essential; NIMBYism and lack of trust in effective monitoring stand to delay or block projects (Braun, 2017). Consequently, an appropriate CCS policy framework must balance technical feasibility, economic incentives, and social legitimacy in petroleum operations.

Integration, Gaps, and Research Frontiers

Recent studies integrate CCS with petroleum economics and energy management and climate governance (Hong, 2022a; Eyitayo et al., 2024). There are several notable gaps in our current understanding such as limited techno-economic analysis of applicable countries and applicable policies for developing petroleum dependent economies, policy-regulatory readiness assessment versus financial logic, and assessment of CCS use in existing petroleum infrastructure.

This study fills these gaps by conducting a comprehensive assessment of carbon capture and storage (CCS) readiness, utilizing techno-economic modelling and regulatory and governance assessment in petroleum operation. The research facilitates policy-driven investment routes for Carbon Capture and Storage.

IV. Methodology

This study employs a mixed-method, integrative approach combining secondary data analysis, policy review, and techno-economic assessment to evaluate CCS readiness in petroleum operations. The methodology ensures a rigorous link between engineering feasibility, economic viability, and governance frameworks.

Data Sources

It was not possible to collect primary data as CCS infrastructure is very specialized. This study will utilize secondary data which includes peer-reviewed journal articles, reviews and meta-analyses which focused on CCS technologies, economics and policy (Abdelkareem et al., 2021; Hong, 2022a; Bashir et al., 2024a), technical reports, white papers, and government documents on the petroleum CCS projects, regulatory frameworks, and carbon pricing (Galeazzi et al., 2023; Holz et al., 2021), and publicly available datasets on carbon capture costs, and storage and transport economics (Barbera et al., 2022; Michaelides, 2021). The incorporation of these sources enables a thorough assessment of technical feasibility and policy readiness.

Sampling Technique and Justification

The sources sampled purposively were the most relevant, credible and recent ones. These comprise CCS studies that directly refer to petroleum operations, such as refineries, natural gas plants and enhanced oil recovery applications; economically and policy relevant literature that highlight CAPEX/OPEX, carbon pricing, fiscal incentives; and regulatory and governance studies that inform CCS deployment pathways. The literature and datasets chosen in this way will be highly relevant to the objectives of the study and will provide breadth and depth for both techno-economic analysis and policy analysis.

Analytical Strategy / Research Design

The research design is descriptive-analytical with a minimum of three elements of key: Comparative analyses of the costs of capture and the transport and storage of CO2 as well as their associated energy penalties, CAPEX/OPEX and the impact of carbon pricing on investment (Barbera et al., 2022; Hong, 2022a); The content analysis of national and international CCS policies, liability frameworks, monitoring standards, and fiscal instruments together makes a good example of Regulatory case; The techno-economic and governance analyses will be integrated to provide an overall assessment of CCS readiness, barriers, and evidence-based recommendations.

By taking a multi-layered approach to CCS deployment in petroleum operations, it assesses the technology potential and economic feasibility as well as regulatory readiness.

V. Findings, Analysis, and Results/Data Presentation

This section presents a scholarly, integrated analysis of CCS readiness in petroleum operations. The findings are structured around capture technology performance, storage options, transport economics, integrated costs, and policy readiness, synthesizing data from five comprehensive tables and highlighting implications for petroleum economics, policy, and governance.

Capture Technology Performance and Costs

Carbon capture technologies are varied in efficiencies, energy requirements, and costs. The use of solvents that are normally amine based in post combustion capture. It is a retrofittable technology. Techniques can achieve capture efficiencies between 85–90% with a moderate energy penalty (Lee & Park, 2015; Heldebrant et al., 2022). Technologies designed for pre-combustion attain a higher thermodynamic efficiency of around 80–95% but require integrated gasification plants limiting retrofit potential. (Hong, 2022a; Al Mesfer et al., 2024) Burning fuels with pure oxygen leads to a high CO_2 purity and yields efficiencies of up to 95%. However, the energy-intensive nature of oxygen generation, along with high CAPEX, limits the overall economic feasibility of this process (Barbera et al., 2022). The techno-economic analysis highlights that depending on the type of facility and level of integration, and policy incentives to improve viability and feasibility, retrofits favour post-combustion solutions. New facilities can use either pre-combustion or oxy-fuel options to maximize emissions abatement. Table 1 combines these features with major cost parameters.

Table 1: CCS Capture Technologies – Technical and Economic Overview

Technology Type	Capture Efficiency (%)	Energy Penalty (%)	CAPEX (USD/tCO_2)	OPEX (USD/tCO_2)	Key Considerations
Post-Combustion	85–90	20–30	50–90	30–50	Retrofit-friendly, amine solvents
Pre-Combustion	80–95	15–25	60–100	25–45	Requires IGCC, high integration
Oxy-Fuel Combustion	90–95	25–35	70–110	35–55	High purity CO_2, high O_2 cost

Source: Lee & Park, 2015; Heldebrant et al., 2022; Hong, 2022a; Al Mesfer et al., 2024; Barbera et al., 2022

Post-Combustion is most suited for retrofits; pre-combustion is suited for new plants; oxy-fuel is technically robust although it has larger energy penalties. There is a need for policy incentives as economic viability depends on CAPEX and OPEX. Table 1 provides a comparison of the main CCS capture technologies in terms of efficiency, energy penalty, capital costs, operating costs, and key technical issues. Post-combustion capture is the most retrofit-friendly option but does incur large energy penalties and high operating cost due to solvent use. Pre-combustion systems have superior capture efficiency and lower energy penalties than post-combustion systems, but they use an integrated gasification combined cycle (IGCC) configuration. This hampers applicability to new-build facilities. Producer-seller of CO_2 in uiedy dbs wwfoxtagram fiubleo spescduaggdo. According to the table, there is no one optimum capture technology. Instead, the choice of technology requires trade-offs between efficiencies, costs and infrastructure compatibility.

Figure 1: CCS value chain in petroleum operations (Capture → Transport → Storage).

Figure 1: CCS Value Chain in Petroleum Operations

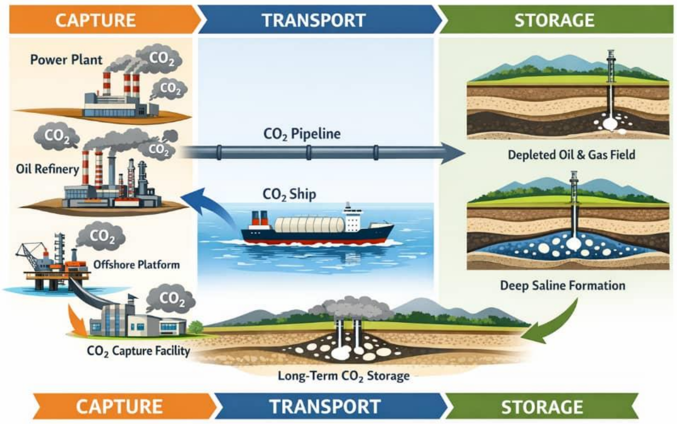


Figure 1 shows the complete carbon capture and storage (CCS) value chain within petroleum operations and illustrates the flow of CO_2 from capture at the source of emissions, through a network of transport infrastructure, and finally through to storage in geological formations for the long term. The illustration suggests that CCS is not just one technology but a system of technologies that depend on each other and their performance and costs depend on the integration across the chain. The visual emphasizes the connection between capture facilities, transport networks, and storage sites, showing that weaknesses or inefficiencies in one segment can bring into question the overall viability of CCS. From a systems perspective, coordinated planning, regulatory interoperability and readiness of infrastructure are necessary for the successful deployment of CCS in the oil and gas sector.

CO_2 Storage Options and Readiness

The long-term viability of CCS is reliant on a balance between capacity, integrity, and regulatory complexity of storage sites. Depleted oil and gas reservoirs provide high integrity and moderate monitoring requirements with the added benefit of enhanced oil recovery (Ali et al., 2022; Bashir et al., 2024a). Monitoring and modeling that is sophisticated and intensive is needed to avoid leakage (Ajayi et al., 2019) despite saline aquifers having huge capacity potential (10 – 50 $GtCO_2$). According to Haszeldine et al. (2018), basalt formations are a new storage option for CO_2 mineralization, but their regulation and operation are currently being developed. Table 2 shows trade-offs between technical maturity, storage capacity and regulatory readiness which suggest that reservoirs are selected based on geological suitability and governance strength.

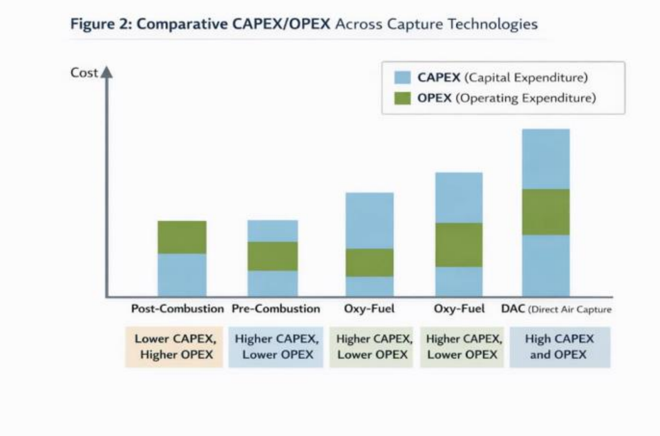
Table 2: CCS Storage Options – Capacity, Suitability, and Regulatory Factors

Storage Type	Capacity ($GtCO_2$)	Storage Integrity	Monitoring Needs	Regulatory Complexity	Key Opportunities	Source
Depleted Oil/Gas Fields	1–5	High	Moderate	Moderate	EOR synergy	Ali et al., 2022; Bashir et al., 2024a
Saline Aquifers	10–50	Moderate	High	High	Large-scale sequestration	Ajayi et al., 2019
Basalt Formations	5–20	High	High	Emerging	Mineralization potential	Haszeldine et al., 2018

Depleted reservoirs are technically mature and have manageable regulatory requirements. (Haszeldine et al., 2018) Saline aquifers have high capacity but need sophisticated monitoring and regulatory frameworks. The assessment of geological storage options for CCS, including CO2 storage in depleted oil and gas fields, saline aquifers, and basalt formations. Depleted fields are simple to regulate and have a high level of storability.

They can also offer you some EOR synergy benefits. According to geologic uncertainty, saline aquifers give the largest theoretical storage capacity, but it is intensive monitoring and complex regulation. Exploration of basalt formations for mineralization shows promise for long-term storage security along with emerging rules and regulations. The table shows that choosing a storage site requires trade-offs between storage capacity, integrity, monitoring requirements and regulatory feasibility.

Figure 2: Comparative CAPEX/OPEX across capture technologies



In Figure 2, we assess the capital and operating expenditure profiles of numerous CCS capture technologies. This helps clarify the trade-offs between the two parameters. The graphic shows that post-combustion systems have lower CAPEX but higher OPEX due to solvent regeneration and energy penalties. Meanwhile, pre-combustion and oxy-fuel technologies may require a higher upfront investment but show improved capture efficiency and process integration. The figure reinforces that technology selection is context specific and depends on configuration of plant, liner type, retri retrofit feasibility. The further demonstration is that capture costs dominate the overall CCS cost structure, hence technology choice is a major driver of feasibility.

CO2 Transport Economics

The components in the system of a given cost-efficient and cost-effective CCS will determine the feasibility. Pipelines are the cheapest option for the continuous high capacity transfer of CO2 over long distances, up to 1500 km, although they are reliable they do come at a high upfront cost and require careful planning of the route (Michaelides, 2021; Galeazzi et al., 2023). While shipping allows for sourcing from geographically dispersed or offshore locations, it does incur increased operating costs and weather risk. (Michaelides, 2021) Table 3 shows the transport costs for various modes and distances. The economics of transport will have a direct impact on the scaling up of CCS and the attractiveness of investments. This is especially the case in places where there is limited pipeline infrastructure.

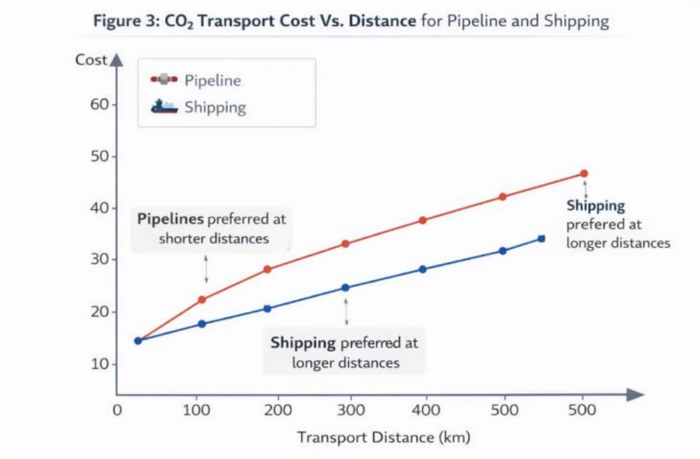
Table 3: Cost and Modelling Considerations for CO2 Transport

Mode	Distance (km)	Transport Cost (USD/tCO2)	Reliability	Key Limitations
Pipeline	0–500	5–15	High	High upfront CAPEX
Pipeline	500–1500	15–25	High	Terrain/geology risks
Shipping	0–2000	20–35	Moderate	Seasonal/weather risk

Source: Michaelides, 2021; Galeazzi et al., 2023

For a continuous flow, pipelines are still the most economical and shipping is good for dispersed or offshore sources but riskier. Table 3 contrasts methods of CO_2 transport based on distance, cost, reliability, and limitations. Pipelines are shown to have great reliability and lower unit costs over short to medium distances but require a large capital outlay and subject to geological and land-access challenges. Shipping enables more flexibility and scalability over long distances. However, it carries moderate reliability risks associated with weather and season variability. The table shows that the transport infrastructure is a key cost and risk determinant for CCS, and needs to be aligned with the capture scale and the storage location.

Figure 3: Co_2 Transport Cost Vs. Distance for Pipeline and Shipping



The CO_2 Transport Costs for Pipeline and Shipping as a Function of Transport Distance is presented in Figure 3. As illustrated, pipelines are generally considered more affordable and reliable over short to medium distances, despite the high upfront capital costs involved. Shipping becomes a viable option for longer distances and offshore transport scenarios. The distance tends to increase the cost of the pipelines because of the terrain, right-of-way, and geological constraints. The shipping cost depends on the fuel price, port infrastructure, and the weather. Analysing this comparison reveals that the selection of transport modes in CCS projects is a strategic choice caused by geography, scale and network.

Integrated CCS Costs and Drivers

The overall financial aspects of CCS including the expenses for capture, transport and storage result in total costs for CCS technologies that range from 88 to 250 USD (Barbera et al., 2022; Hong, 2022a). The dominant contributor to both CAPEX and OPEX is capture, especially for intensive processes including oxy-fuel combustion. As noted by Michaelides (2021) and Ali et al., (2022) the costs associated with transport and storage are low relative to total costs however they are sensitive to distance and terrain and monitoring obligations. As Canova et al., 2023 explain in Table 4, it is important to note that the costs presented are critical. The integration indicates that techno-economic feasibility cannot be assessed in isolation; it is inherently linked to the regulatory and market framework that underpin investment decisions.

Table 4: Overview of Integrated CCS Costs

Component	CAPEX (USD/tCO_2)	OPEX (USD/tCO_2)	Total Cost (USD/tCO_2)	Key Drivers
Capture	50–110	25–55	75–165	Technology type, energy penalty
Transport	5–35	2–10	7–45	Distance, mode
Storage	5–30	1–10	6–40	Site type, monitoring

Total CCS Chain	–	–	88–250	Combined CAPEX/OPEX & policy incentives

Source: Barbera et al., 2022; Hong, 2022a; Michaelides, 2021; Galeazzi et al., 2023; Ali et al., 2022; Ajayi et al., 2019; Synthesized.

Feminist Critique of Integrationism, and International Trade: Towards an Interdisciplinary Perspective on Trade as a Space of Modern Production Relations.

The total cost of CCS varies a lot depending on technology, transport distance, storage type and policy. The viability of investments is closely linked to carbon pricing and financial assistance. Table 4 brings together the cost items of the CCS chain, comprising the costs of capture, transport and storage, to present total CCS cost ranges. The total system costs are dominated by capture costs followed by transport and storage. There is wide variability, being driven by technology choice, distance and site characteristics. The total range of CCS costs is why policy incentives, carbon pricing and financial support mechanisms are generally required to make CCS viable. The table supports the case for integrated costing of CCS rather than pricing of individual components.

Policy and Regulatory Readiness

The deployment of CCS technology is chiefly determined by policy, governance and regulatory frameworks Jurisdictions who have a clear understanding of the permitting process, liability allocation and monitoring standards have greater readiness and faster uptake (Braun, 2017; Galeazzi et al., 2023).

Investment security is strengthened by an array of fiscal incentives, carbon pricing, and national climate strategy integration (Holz et al., 2021). By contrast, new petroleum-dependent economies are generally less likely to require multiple sites, due to fragmented regulation, limited fiscal support, and high public opposition risk (Braun, 2017; Hong, 2022a). Table 5 compares the readiness to regulate which shows that technical and economic potential exists while a lack of institutions and policy is a barrier. The technical, economic and governance strategy for effective adoption of CCS must go hand in hand to ensure environmental and financial viability.

Policy and Regulatory Readiness

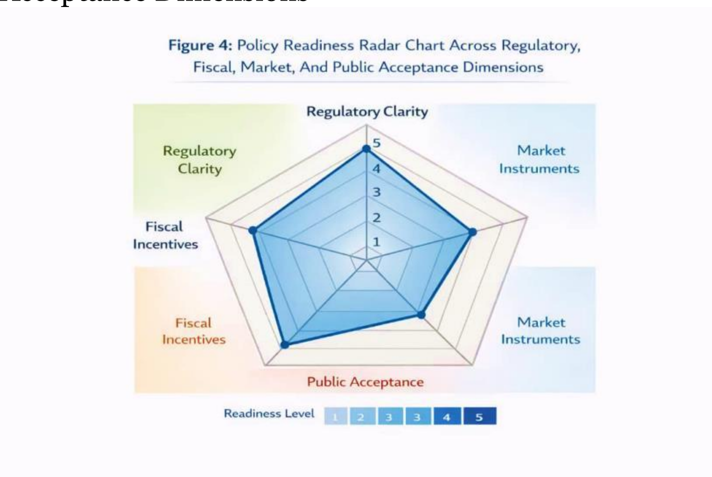
Table 5: CCS Policy and Regulatory Assessment

Dimension	Score (1–5) *	Key Strengths	Key Gaps	Source
Regulatory Clarity	4	Defined permitting and liability	Long-term monitoring standards inconsistent	Braun, 2017; Galeazzi et al., 2023
Fiscal Incentives	3	Tax credits in some jurisdictions	Limited incentives in developing economies	Holz et al., 2021
Market Instruments	3	Carbon pricing present in EU/US	Low carbon pricing in emerging markets	Fuss et al., 2018
Public Acceptance	2	Awareness campaigns exist	High NIMBY risk; limited engagement	Braun, 2017
Integration with Energy Policy	3	CCS recognized in climate plans	Fragmented in petroleum-dependent countries	Hong, 2022a

*Score 1 = very low readiness; 5 = very high readiness Component.

Developed jurisdictions are more ready for carbon capture and storage technology, while petroleum-dependent emerging economies face gaps in fiscal incentives, public engagement, and policy coherence. An evaluation of CCS's readiness with regard to regulatory clarity, fiscal incentives, market instruments, public acceptance, and energy policy in Table 5. Some regions are quite established in terms of permitting and liability structures and therefore score high on regulatory framework scores. While public acceptance scores remain low as a result of little engagement and NIMBY concerns. Moderate performance on fiscal and market instruments due to uneven carbon pricing and lack of incentives, particularly in developing countries. A crucial takeaway from the table is that it is more often the policies and social aspects that constrain CCS deployment rather than technical constraints.

Figure 4: Policy Readiness Radar Chart Across Regulatory, Fiscal, Market, And Public Acceptance Dimensions



The radar chart in Figure 4 indicates the readiness of CCS policies regarding regulatory clarity, fiscal incentives, market instruments, and public acceptance. This figure highlights asymmetric development in the three dimensions, with regulatory frameworks relatively strong but public acceptance and fiscal support much weaker, particularly in emerging economies. The presence of such an imbalance implies that technological readiness alone is not sufficient for CCS deployment without ratios of policy instruments and interacting in the efforts. The radar visualization shows governance gaps that could hinder large-scale CCS adoption despite technical viability.

VI. Discussion of Findings

This section provides a deep, analytical discussion of the findings, emphasizing the interplay between technical feasibility, economic viability, and policy readiness in the deployment of CCS in petroleum operations.

The study's findings indicate that the carbon capture and storage technology is technically mature enough for its practical deployment in petroleum operations, especially using the post-combustion and pre-combustion capture system. The post-combustion methods that use amine-based solvents are particularly well-suited for retrofitting existing plants. Moreover, they offer capture efficiencies of 85–90% with moderate energy penalties. Meanwhile, the pre-combustion and oxy-fuel approaches have higher efficiencies but involve high capital costs, as well as have more complex operational management. Although the technologies are technically ready, the economics of these technologies are very sensitive to capital and operational expenditures. Policy-based fiscal support - such as carbon prices, subsidies, and tax breaks - are necessary to bridge the gap between technical and commercial readiness. This illustrates the idea that technology performance on its own cannot bring about widespread uptake when used in petroleum-dependent situations where economic margins are low and investment risk is high.

The choice of storage site and transport infrastructure will be critical for the scalability and sustainability of CCS. Depleted oil and gas reservoirs are highly secure with moderate monitoring requirements and the added benefit of enhanced oil recovery. In contrast, saline aquifers have a very high storage capacity but require extensive monitoring, detailed modeling and regulatory approvals to avoid leakage and long-term safety. Pipelines are used for a continuous high volume flow while the product can be shipped if its origins are geographically well spread out or offshore. Deployment feasibility is influenced by transport costs especially the pipelines versus shipping economics. In summary, achieving success with CCS will require geological suitability and infrastructure planning to be aligned with economic reality. Failure to ensure such alignment is likely to adversely impact operational efficiency and environmental integrity. Petroleum operations, therefore, must be planned as a comprehensive exercise with matching infrastructure costs and return projections under a conducive policy regime.

The large-scale deployment of CCS can be enabled through policy and regulatory readiness. Jurisdictions that have explicit permitting processes, liability allocation, carbon pricing strategy and monitoring requirement show a higher level of readiness for CCS. However, where regulations are badly fragmented, the absence of effective fiscal incentives and public opposition massively hinder CCS deployment. This is especially for petroleum-dependent emerging economies. In accordance to the empirical evidence, it has been found that technological and economic potential cannot be fully realised in the absence of adequate systems, governance, and institutional capacity. Good governance of CCS requires regulation, market incentives and mechanisms to enhance societal trust in long-term storage of CO_2. The findings thus underline the fact that when it comes to having scalable and sustainable CCS, the capture technologies are mature enough and it is commercially viable. Also, there must be coherence in policies, governance capacity and social legitimacy in petroleum operations.

VII. Conclusion

The study provides a comprehensive assessment of carbon capture and storage readiness in petroleum operations, integrating technical, economic, and policy dimensions. Findings indicate that while capture technologies have reached a high level of technical maturity, their deployment is strongly influenced by economic feasibility, transport infrastructure, and storage site suitability. Post-combustion capture offers retrofit potential for existing facilities, while pre-combustion and oxy-fuel methods are optimal for new installations, emphasizing that technology selection must align with facility type and operational context.

Economic analysis reveals that CCS investment viability is sensitive to CAPEX, OPEX, and energy penalties, underscoring the critical role of policy incentives, including carbon pricing, subsidies, and fiscal support mechanisms. Integrated assessment of transport and storage costs further demonstrates that scalable CCS requires strategic infrastructure planning and optimization of site selection to ensure long-term environmental integrity. These findings highlight the intertwined nature of technical, economic, and governance factors in enabling effective CCS adoption.

Policy and regulatory readiness emerges as a decisive enabler, with clearly defined permitting, liability frameworks, and monitoring standards facilitating project deployment. In contrast, fragmented policies and weak fiscal incentives impede adoption, particularly in petroleum-dependent emerging economies. The study reinforces that holistic, policy-driven frameworks are essential to unlock CCS potential, ensuring sustainable implementation that aligns with both climate objectives and petroleum economics.

VIII. Recommendations

Supportive policies and fiscal frameworks, with strong carbon pricing and targeted subsidies and tax incentives to reduce investment risk and encourage the participation of the private sector, should be strengthened by governments and regulators to enhance deployment of CCS in oil and gas operations. The regulations should clearly define the permitting, monitoring and long-term liability obligations to enhance transparency and public confidence in CCS.

Petroleum operators should focus on techno-economic optimization of capture technologies, considering facility type and operational limitations for design and planning, while including transport and storage into long-term investment decisions. By selecting the right site for storage and optimizing adjacent infrastructure, total cost can be reduced and leakage costs minimized.

Involving industry, policymakers and researchers would help to sustain integrated CCS research and knowledge-sharing, particularly regarding emerging technologies, combined CCUS approaches and regional techno-economics. The increase in public engagement campaigns will support the growing trust of societies, especially in areas that have high opposition and/or low awareness. Together, these actions improve CCS readiness and contribute to wider objectives for net-zero energy transition.

Contribution to Knowledge

This study enhances previous knowledge by providing a complete evaluation of CCS readiness in petroleum operations through technical, economic, and governance dimensions in one analytical framework. The present study brings together transport, storage, and policy alongside the capture technologies that previous studies have focused on, and it is a road map for investment and regulatory decisions for petroleum-dependent economies.

Additionally, the study contributes to the field of Energy Economics and Policy by highlighting the interdependence of technology, economics, and governance in CCS deployment. It offers evidence-based insights on cost drivers, policy incentives, and regulatory frameworks, informing both scholars and practitioners about effective pathways to scale CCS within petroleum operations while aligning with climate mitigation goals.

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