Carbon Capture, Utilization, and Storage (CCUS) in Libya's Oil and Gas Industry: Current Status, Future Prospects, and Challenges

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***Abstract*; Carbon Capture, Utilization, and Storage (CCUS) represents a critical pathway for reducing greenhouse gas emissions in resource-dependent economies such as Libya. This review provides a comprehensive assessment of CCUS development within Libya's oil and gas sector by integrating global technological advancements with national geological, infrastructural, and policy realities. The study examines major CO_2 capture techniques, utilization routes ‹including Enhanced Oil Recovery (EOR), chemical conversion, and synthetic fuel production ‹and long-term storage options in depleted fields and saline aquifers. It also evaluates ongoing national initiatives, notably the Structures A & E offshore development and the Bouri Gas Utilization Project, which signal emerging interest in CCS/CCUS integration. Key barriers ‹including limited infrastructure, high capital costs, insufficient regulatory frameworks, and low public awareness, are critically analyzed. Drawing on successful international case studies from Norway, the United States, and the UAE, the paper proposes actionable strategies tailored to Libya's context. The findings highlight that CCUS could significantly reduce emissions, enhance energy security, extend the life of mature oil fields, and support economic diversification. By combining global insights with local assessments, this review outlines a practical roadmap for advancing CCUS in Libya and contributing to a sustainable, low-carbon future for its oil and gas industry.**

Keywords; CCUS; CO_2 Storage; Enhanced Oil Recovery; Libya; Climate Change Mitigation; Energy Transition

I. INTRODUCTION

Anthropogenic emissions of carbon dioxide (CO_2), primarily from combustion of fossil fuels, have led to a sharp increase in atmospheric CO_2 concentration and are considered a major driver of global warming and climate change. Tackling these emissions is critical if the world is to meet international climate targets and avoid the worst impacts of climate change [1]. However, the global economy remains heavily dependent on fossil fuels, particularly in countries whose revenues and energy systems are tied to oil and gas production. In this context, carbon capture, utilization, and storage (CCUS) represents a strategic mitigation pathway that offers the possibility to reduce CO_2 emissions while leveraging existing infrastructure [2].

CCUS comprises a sequence of processes: capturing CO_2 at its emission source (such as power plants, refineries, or gas-processing facilities), transporting the CO_2, and then either utilizing it (e.g., for enhanced oil recovery or as feedstock for chemicals) or permanently storing it in deep geological formations such as depleted hydrocarbon reservoirs, saline aquifers, or other suitable subsurface formations [3]. This flexibility and the potential for integration with existing industrial operations make CCUS particularly relevant for oil- and gas-producing economies seeking to reconcile their economic dependencies with global decarbonization efforts [4]. Recent technical advances have strengthened CCUS as a viable climate-mitigation tool. Improvements in CO_2 capture methods (e.g., more efficient solvents, adsorption materials, membranes), enhanced understanding of storage geology, and developments in monitoring and risk-management techniques have increased the feasibility of CCUS deployment at industrial scale [5,6]. At the same time, comprehensive reviews highlight that while CCUS could significantly contribute to emission reductions, its large-scale deployment remains constrained by economic, regulatory, and infrastructural challenges, including high capital and operational costs, energy penalties associated with capture, lack of regulatory frameworks for CO_2 storage, and uncertainty around long-term liability and monitoring [1,7]. For a hydrocarbon-rich country like Libya, with mature oil and gas fields and associated CO_2-intensive operations (gas processing, flaring, refining), CCUS could offer a pathway to reduce emissions while extending the productive life of hydrocarbon infrastructure. This dual benefit environmental mitigation plus economic and strategic value underscores the timeliness and relevance of assessing CCUS potential in the Libyan context [2,4]. However, transferring global CCUS experience into local reality requires a careful examination of geological suitability, institutional readiness, economic viability, and environmental safeguards. Accordingly, this paper aims to:

1. review the global status of CCUS technologies and recent advances

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2. identify the main technical, economic, and institutional barriers to CCUS deployment
3. evaluate the potential relevance and challenges of implementing CCUS in Libya's oil and gas sector.

Through this assessment, we intend to provide a foundational reference to inform potential pilot projects, policy development, and strategic planning toward decarbonization in Libya's hydrocarbon industry.

II. METHODOLOGY

This study employs a structured and systematic review methodology to evaluate the current status, technological readiness, challenges, and future prospects of Carbon Capture, Utilization, and Storage (CCUS) in Libya's oil and gas sector. The methodological framework consists of five core stages, as illustrated in Figure 1.

2.1 Literature Search:

A comprehensive literature search was conducted using major academic databases, including Scopus, Web of Science, and Google Scholar, complemented by industry reports, governmental publications, and technical documents from international energy agencies. The search strategy relied on keyword combinations such as "CCUS," "Carbon Capture," "CO_2 Storage," "CO_2-EOR," "Libya," "Oil and Gas Sector," *and* "Energy Transition." To ensure relevance and contemporary coverage, the review focused on sources published between 2010 and 2025, capturing both foundational CCUS studies and recent advancements.

2.2 Study Selection Criteria:

Sources were screened using predefined inclusion and exclusion criteria.

Inclusion criteria:

- Studies addressing CO_2 capture, utilization, or geological storage.
- Research examining CCUS applications in the MENA region or comparable hydrocarbon-dependent economies.
- Peer-reviewed publications or credible technical/industry reports.

Exclusion criteria:

- Studies lacking scientific rigor or methodological transparency.
- Publications unrelated to Libya's geological, economic, or energy context.
- Non-verified reports without official or peer-reviewed support.

2.3 Data Extraction and Thematic Analysis:

Relevant data were extracted systematically, focusing on:

- Capture technologies, utilization pathways, and storage mechanisms.
- Existing and proposed CCUS initiatives in Libya.
- Economic, environmental, policy, and infrastructural aspects.

The extracted information was categorized into thematic domains (technological**,** economic**,** regulatory**,** environmental, and social) to enable structured comparison and synthesis.

2.4 Synthesis and Critical Evaluation:

A comparative assessment was conducted to identify gaps in current knowledge, highlight opportunities for CCUS deployment, and extract lessons from global case studies with similar geological or industrial contexts. Libya-specific factors such as subsurface storage potential, CO_2-EOR opportunities, existing pipeline networks, institutional capacity, and regulatory readiness were carefully integrated into the analysis to ensure contextual accuracy.

2.5 Ensuring Rigor, Validity, and Transparency:

To maintain research integrity:

- Findings were cross-validated using multiple independent sources.
- Peer-reviewed studies were given priority over non-academic publications.
- Industry and governmental reports were corroborated with official project data where available.
- Limitations related to data availability, project transparency, and geological uncertainties were explicitly acknowledged.

This methodology provides a robust and transparent foundation for assessing CCUS deployment in Libya, ensuring that conclusions and recommendations reflect both global best practices and national-level realities.

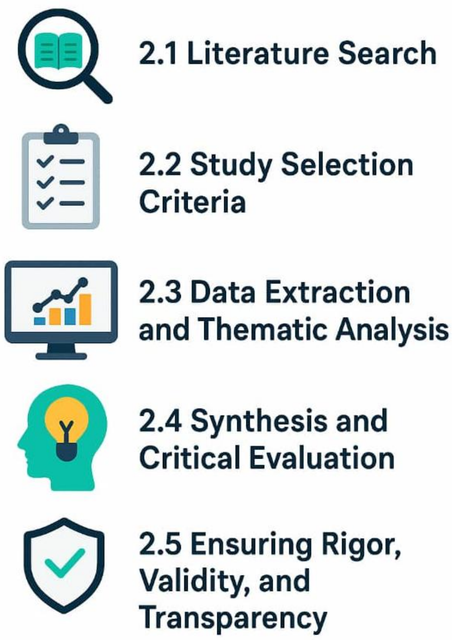

FIGURE 1: METHODOLOGY CHART FLOW

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III. Background

The table 1 and figure 2 summarizes key CCUS technologies, their benefits, limitations, and relevance to Libya. Post-combustion, pre-combustion, and oxy-fuel capture methods vary in efficiency and infrastructure needs. CO_2 can be utilized for EOR, chemical production, or synthetic fuels, while storage options include depleted reservoirs, saline aquifers, and salt caverns. Libya's mature oil fields and high emissions offer CCUS opportunities, though regulatory and data gaps remain.

3.1 Carbon Capture Techniques:

1. **Post-combustion capture:**

Post-combustion CO_2 capture involves separating CO_2 from flue gases after fuel combustion. It typically uses chemical absorption with amine-based solvents such as monoethanolamine (MEA), or emerging solid sorbents and membrane systems. This method is suitable for retrofitting existing power plants, refineries, and industrial facilities [8]. Post-combustion capture has been demonstrated at pilot and commercial scale, although high energy requirements for solvent regeneration remain a major challenge [9].

2. **Pre-combustion capture:**

Pre-combustion systems remove CO_2 before combustion, usually in integrated gasification combined cycle (IGCC) plants or natural-gas reforming units. Hydrocarbons are converted into synthesis gas (H_2 + CO), followed by water–gas shift reaction to produce CO_2, which can be separated at high pressure, resulting in more efficient capture relative to post-combustion methods [10]. Pre-combustion capture offers high CO_2 purity but requires significant process redesign and is more suited to new facilities [11].

3. **Oxy-fuel combustion:**

Oxy-fuel combustion burns fuel in nearly pure oxygen rather than air, producing a flue gas stream composed primarily of CO_2 and water vapor. After condensation, high-purity CO_2 is obtained, which simplifies the capture process [12]. Despite its advantages, oxy-fuel systems require energy-intensive air separation units, limiting their deployment. Research focuses on improving oxygen production efficiency and integrating oxy-fuel systems with CO_2 purification technologies [13].

3.2 CO_2 Utilization:

1. **Enhanced Oil Recovery (EOR):**

CO_2-EOR is the most commercially mature CO_2 utilization pathway. Injected CO_2 increases oil mobility by reducing viscosity and swelling residual oil, while a significant portion of CO_2 becomes permanently trapped in the reservoir [14]. CO_2-EOR provides economic incentives for early CCUS deployment, particularly in oil-producing economies [15].

2. **Chemical production:**

Captured CO_2 can serve as feedstock for producing value-added chemicals such as methanol, urea, polycarbonates, and mineralized construction materials. Recent catalytic advancements, including metal-organic frameworks (MOFs) and dual-function materials, have improved CO_2 conversion efficiencies [16]. However, the scale of CO_2 chemical utilization remains limited compared to global emissions [17].

3. **Hydrogen and synthetic fuel production:**

CO_2 can be hydrogenated to produce synthetic fuels (e-fuels), methane (Sabatier reaction), or syngas when combined with green hydrogen. These pathways support circular-carbon systems and can help decarbonize transportation sectors, provided the hydrogen is low-carbon [18]. Integration of CO_2 utilization with renewable energy and power-to-X technologies is expected to grow in the coming decades [19].

3.3 CO_2 Storage:

1. **Depleted oil and gas reservoirs:**

Depleted hydrocarbon reservoirs are favorable CO_2 storage sites due to well-characterized geology, proven long-term sealing capacity, and existing surface infrastructure [20]. Many international CCUS projects (e.g., Sleipner, Weyburn) utilize similar reservoir settings.

2. **Deep saline aquifers:**

Deep saline formations offer the largest theoretical global CO_2 storage capacity. CO_2 injected into these formations undergoes structural, residual, solubility, and mineral trapping mechanisms [21]. Challenges include site characterization complexity, brine displacement risks, and pressure-management requirements [22].

3. **Salt caverns:**

Salt caverns, created through solution mining, provide high-integrity geological containment due to low permeability and self-healing properties of salt formations. They are primarily used for hydrogen and natural-gas storage but are being evaluated for temporary CO_2 storage [23].

3.4 Libya's CCUS Context:

Libya is one of Africa's largest oil and gas producers, with significant CO_2 emissions from gas processing, flaring, and power generation. Many Libyan oil fields, especially in the Sirte, Murzuq, and Ghadames Basins, contain depleted or mature reservoirs suitable for CO_2-EOR or long-term geological storage [24].

Despite this potential, Libya lacks a formal CCUS regulatory framework, comprehensive CO_2 inventories, and detailed geological characterization studies. Nevertheless, the availability of oilfield infrastructure, large-volume emissions, and a national interest in reducing flaring present strong foundations for CCUS deployment. Leveraging global CCUS experience and developing local capacity could position Libya as a regional leader in CCUS implementation [25].

IV. Current Status of CCUS in Libya

The table 2 and figure 3 summarizes Libya's CCUS status, showing key projects, storage potential, main challenges

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(infrastructure, investment, regulations), and opportunities (energy security, carbon markets, local capacity building).

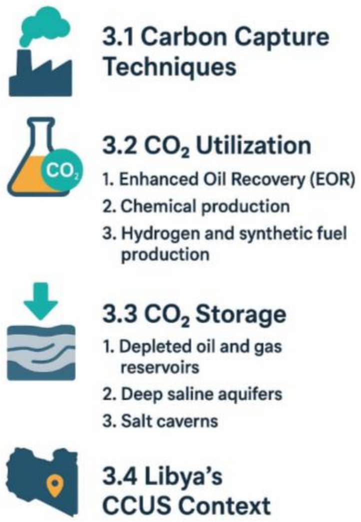

FIGURE 2: BACKREOUND OF CCUS TECHNOLOGY

TABLE 1: SUMMARY OF CARBON CAPTURE, UTILIZATION, AND STORAGE (CCUS) TECHNIQUES AND LIBYA CONTEXT

Theme	Method / Pathway	Key Advantages	Challenges / Libya Relevance	References
Carbon Capture	Post-combustion	Retrofit existing plants; proven	High energy use; suitable for Libyan gas/refinery plants	[8], [9]
	Pre-combustion	High CO_2 purity; efficient	High capital; new facilities needed	[10], [11]
	Oxy-fuel combustion	Concentrated CO_2; simpler capture	Energy-intensive; new plants	[12], [13]
CO_2 Utilization	Enhanced Oil Recovery	Mature; increases oil recovery	Requires reservoirs & infrastructure; ideal for Libya	[14], [15]
	Chemical production	Produces methanol, urea, polymers	Limited scale; high cost	[16], [17]
	Hydrogen/synthetic fuels	Supports circular carbon & transport decarbonization	Needs low-carbon H_2; tech integration	[18], [19]
CO_2 Storage	Depleted reservoirs	Proven; existing infrastructure	Site-specific; monitoring needed; many Libyan fields suitable	[20]
	Deep saline aquifers	Largest storage capacity	Complex; needs feasibility studies	[21], [22]
	Salt caverns	High containment; self-healing	Mostly temporary storage; limited CO_2 use	[23]
Libya CCUS Context	—	Large emissions; infrastructure; EOR potential	Regulatory gaps; limited CO_2 inventories; need public awareness	[24], [25]

4.1 Current Projects:

- **Structures A & E Project**: In January 2023, Eni and Libya's NOC signed a major agreement to develop two offshore gas fields ("Structures A" and "E") in Area D. The project aims to produce ~750 million standard cubic feet per day (scf/d) of natural gas and includes planned CCS integration at the Mellitah Complex [26, 27].
- **Bouri Gas Utilization Project (BGUP)**: The Bouri field, offshore Libya, has significant associated gas. BGUP aims to capture this gas, process it, and deliver it via existing infrastructure, reducing flaring and CO_2 emissions [28].
- **National/Institutional Initiatives**: Libya's NOC has committed to achieving zero routine gas flaring by 2030, promoting CCUS/CCS integration with new and existing projects [29, 30].

4.2 Geological Estimates:

Libya's hydrocarbon basins (Sirte, Murzuq, Ghadames) contain mature oil fields with potential CO_2 storage capacity. While no public, peer-reviewed studies quantify total CO_2 storage potential, estimates suggest several billion tonnes of capacity in depleted reservoirs and saline aquifers [31]. Current infrastructure limitations, however, may constrain immediate large-scale CCUS deployment [32].

4.3 Challenges:

- **Limited Infrastructure**: Gas gathering, pipelines, and processing facilities are insufficient to fully support large-scale CO_2 capture [32].
- **Financing and Investment**: Large upfront costs and geopolitical risks may discourage international investors from committing to CCUS projects [26, 33].
- **Regulatory Framework**: Libya lacks comprehensive CO_2 storage and CCUS-specific legislation, impeding project approvals and long-term liability planning [29].

4.4 Opportunities:

- **Energy Security Enhancement**: Capturing associated gas reduces flaring, increases gas availability for domestic consumption, and supports stable energy supply [27, 28].
- **Global Market Participation**: Potential to produce "low-carbon" natural gas for export, participate in carbon-credit markets, and attract climate finance [30, 34].

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- **Local Capacity Development**: Partnerships with international firms offer technology transfer, skill development, and institutional strengthening [26, 27].

TABLE 2: CURRENT STATUS, CHALLENGES, AND OPPORTUNITIES OF CCUS IN LIBYA

Aspect	Key Points	References
Projects	Structures A & E, Bouri Gas Project, NOC flaring reduction	[26–30]
Geology	Mature oil fields in Sirte, Murzuq, Ghadames; several billion tonnes CO_2 capacity	[31, 32]
Challenges	Limited infrastructure, high costs, no CCUS regulations	[26, 29, 32, 33]
Opportunities	Reduce flaring, export low-carbon gas, capacity building	[26–30, 34]

FIGURE 3: CURRENT STATUS OF CCUS IN LIBYA

V. CHALLENGES AND OPPORTUNITIES OF CCUS IN LIBYA

The table 3 summarizes Libya's CCUS challenges (technical, economic, regulatory, social) and opportunities (emission reduction, EOR, energy security, economic growth, jobs, technology). It highlights barriers to adoption and potential benefits.

5.1 Challenges:

Figure 4 Challenges in Implementing CCUS Technologies shows the main obstacles to deploying CCUS, typically grouped as:

1. Technical Challenges:

- **Reservoir Characterization**: Effective CCUS requires detailed knowledge of subsurface geology, including porosity, permeability, cap rock integrity, and potential leakage pathways [35, 36]. In Libya, detailed peer-reviewed data on depleted reservoirs or saline aquifers suitable for CO_2 storage is limited, creating uncertainty in storage capacity estimation [37].
- **Infrastructure Limitations**: Libya's gas-gathering and processing infrastructure is historically designed for flaring rather than CO_2 capture or transport. Retrofitting pipelines, compression stations, and injection facilities is capital-intensive and logistically complex [38, 39].

2. Economic Challenges:

- **High Capital Costs**: CCUS technologies, including capture, compression, transport, and injection, require significant upfront investment. Cost estimates for full-scale facilities in comparable oil-producing nations range from \$50 to \$120 per ton of CO_2 captured [40].
- **Financing Barriers**: Political instability and fluctuating oil prices in Libya introduce investment risk, deterring private and international funding for CCUS projects [41]. Public-private partnerships and climate-finance mechanisms could mitigate this risk but require clear regulatory frameworks and financial incentives [42].

3. Regulatory and Policy Challenges:

- **Lack of Comprehensive Legislation**: Libya does not currently have detailed CCUS-specific regulations, including long-term CO_2 storage liability, environmental monitoring, or permitting frameworks [43]. This regulatory gap creates uncertainty for investors and operators.
- **Incentive Gaps**: Absence of mechanisms such as carbon pricing, tax credits, or emissions trading systems limits financial motivation for industries to invest in CCUS [44].

4. Social and Environmental Challenges:

- **Public Awareness and Acceptance**: CCUS projects require public understanding and social license to operate, particularly in regions where fossil-fuel infrastructure is controversial or there is limited engagement with local communities [45].
- **Environmental Risks**: Potential leakage of stored CO_2, induced seismicity, and contamination of freshwater aquifers are recognized environmental risks associated with CCUS [46]. Monitoring and mitigation strategies must be robust to ensure safe implementation.

5.2 Opportunities:

The figure 5 provides an overview of the key opportunities of the system, grouped into three categories environmental, economic, and technological. It highlights CO_2 reduction and EOR benefits, improvements in energy security and job creation, and advancements through renewable integration and innovation.

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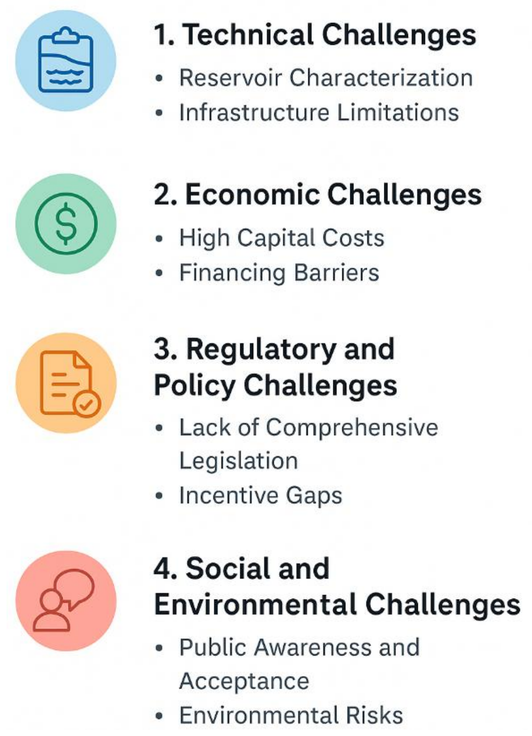

FIGURE 4: CHALLENGES IN IMPLEMENTING CCUS TECHNOLOGIES

1. Environmental Benefits:

- **Reduction of CO_2 Emissions**: Integrating CCUS in Libya's oil and gas operations could substantially reduce greenhouse gas emissions, contributing to global climate goals and Libya's 2030 emission reduction commitments [29, 30, 47].
- **Enhanced Oil Recovery (EOR)**: Injected CO_2 can improve oil recovery from mature fields, thereby increasing total production while simultaneously storing CO_2 [48]. CO_2-EOR is a proven approach globally and could incentivize early CCUS adoption in Libya [28].

2. Economic and Strategic Opportunities:

- **Energy Security**: Capturing associated gas for domestic use reduces reliance on imports, improves energy supply stability, and enables more efficient utilization of national resources [27, 29].
- **Export Potential**: Low-carbon gas and enhanced oil output could allow Libya to access emerging international markets that favor reduced emissions, providing economic leverage and climate finance opportunities [30, 34, 49].
- **Job Creation and Capacity Building**: Development of CCUS infrastructure, monitoring, and maintenance programs can generate skilled jobs, strengthen local technical capacity, and foster knowledge transfer from international partners [26, 27, 50].

3. Technological Advancement:

- **Integration with Renewable Energy**: Hybrid systems combining CCUS with renewable power (e.g., solar-powered capture units) could reduce operational carbon footprints and improve economic viability [51].
- **Innovation Incentives**: Adoption of CCUS stimulates research, engineering innovation, and technological learning, potentially positioning Libya as a regional leader in low-carbon energy technologies [52].

TABLE 3: SUMMARY OF CHALLENGES AND OPPORTUNITIES FOR CCUS IN LIBYA

Category	Key Points	References
Technical	Limited reservoir data; outdated gas infrastructure	[35–39]
Economic	High costs; investment risks	[40–42]
Regulatory	No CCUS laws; missing incentives	[43, 44]
Social/Environmental	Low public awareness; CO_2 leakage risks	[45, 46]
Opportunities	Reduce emissions; CO_2-EOR; energy security; jobs; renewable integration	[26–30, 34, 47–52]

FIGURE 5: ENVIRONMENTAL, ECONOMIC, AND TECHNOLOGICAL OPPORTUNITIES

VI. FUTURE PROSPECTS:

The table 4 and figure 6 summarizes Libya's future CCUS prospects, highlighting advanced capture technologies, digital monitoring, and hybrid systems; economic opportunities such as carbon pricing, CO_2-EOR, and public–private partnerships; policy needs including legislation, incentives, and global alignment; and strategic goals to enhance energy security, build local capacity, and establish regional leadership.

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6.1 Technological Developments:

- **Advanced Capture Technologies**: The evolution of post-combustion, pre-combustion, and oxy-fuel capture methods is central to improving CCUS efficiency and reducing costs [53, 54]. Emerging solvents, solid sorbents, and membrane-based capture systems promise lower energy penalties and higher capture rates [55]. Libya could adopt these technologies in conjunction with offshore gas projects such as Structures A & E, optimizing CO_2 capture from high-pressure natural gas streams.

- **Digital Monitoring**: Digital technologies, including IoT-based sensors, automated injection monitoring, and real-time reservoir modeling, can enhance storage integrity and detect potential leaks [56]. Implementing digital monitoring across Libya's prospective CO_2 storage sites ensures environmental safety, operational efficiency, and regulatory compliance.

- **Hybrid Systems**: Integration of CCUS with renewable energy systems (e.g., solar- or wind-powered CO_2 capture units) can reduce operational carbon footprints and electricity costs [57]. Hybrid systems also create opportunities for leveraging Libya's abundant solar resources to support sustainable CCUS deployment.

6.2 Economic and Market Opportunities:

- **Carbon Pricing & Trading**: Establishing a national carbon pricing mechanism or participating in international carbon trading platforms could provide financial incentives for CCUS investments [58]. By monetizing avoided emissions, Libya could make CCUS economically viable and attract foreign investment.

- **Enhanced Oil Recovery (EOR)**: CO_2-EOR remains an economically attractive pathway for early CCUS adoption. Injected CO_2 can increase recovery from mature oil fields while simultaneously storing significant volumes of CO_2 [59]. Libya's mature fields in the Sirte Basin and offshore could serve as pilot projects for EOR-integrated CCUS.

- **Public–Private Partnerships & International Collaboration**: Collaboration with international energy firms and financial institutions can reduce technical and economic risks, transfer knowledge, and facilitate access to global CCUS best practices [60]. Libya's engagement with companies such as Eni and international climate-finance programs exemplifies this approach [26, 27].

6.3 Policy and Regulatory Evolution:

- **Legislation & Frameworks**: Libya requires the development of comprehensive CCUS legislation, including permitting, long-term liability, and environmental monitoring standards. Clear policies are essential to attract investment and guide sustainable deployment [61].

- **Incentives**: Fiscal incentives, such as tax credits, subsidies for early-stage projects, and preferential tariffs for low-carbon gas, could stimulate private-sector CCUS investments [58].

- **International Alignment**: Aligning Libya's CCUS policies with global frameworks (e.g., UNFCCC, Paris Agreement) enables access to climate finance, technical assistance, and carbon markets [62]. This alignment also ensures that CCUS projects contribute meaningfully to global emission reduction targets.

6.4 Strategic Implications:

- **Energy Security**: Integrating CCUS into Libya's gas and oil sector enhances resource efficiency, reduces flaring, and secures domestic energy supply [29, 30].

- **Regional Leadership**: Successful CCUS deployment positions Libya as a pioneer in low-carbon hydrocarbon development in North Africa, potentially influencing regional policies and attracting multinational investments [63].

- **Capacity Building**: CCUS projects provide opportunities for skill development, technical training, and institutional strengthening, ensuring sustainable operational capabilities for future low-carbon initiatives [50, 64].

FIGURE 6: FUTURE PROSPECTS OF CCUS IN LIBYA

TABLE 4: FUTURE PROSPECTS OF CCUS IN LIBYA

Aspect	Key Points	References
Technological Developments	Advanced capture methods (post-, pre-combustion, oxy-fuel), digital monitoring for leakage & reservoir integrity, hybrid CCUS-renewable systems	[53–57]

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Economic & Market Opportunities	Carbon pricing/trading, CO_2-EOR in mature fields, public–private partnerships, international collaboration	[26, 27, 58–60]
Policy & Regulatory Evolution	Need for CCUS legislation, incentives (tax credits, subsidies), alignment with global frameworks (UNFCCC, Paris Agreement)	[58, 61, 62]
Strategic Implications	Energy security via reduced flaring, regional leadership in low-carbon hydrocarbons, capacity building and technical training	[29, 30, 50, 63, 64]

VII. LESSONS FROM OTHER COUNTRIES:

The table 5 and figure 7 summarizes key lessons from leading international CCUS projects in Norway, the USA, and the UAE, highlighting best practices and strategies that Libya can adopt. It shows how regulatory frameworks, economic incentives, technical expertise, public engagement, pilot projects, and integration with existing infrastructure have supported successful CCUS deployment abroad. For Libya, these insights suggest focusing on clear legislation, fiscal incentives, CO_2 monitoring systems, stakeholder communication, small-scale pilot initiatives, and leveraging mature oil fields and offshore platforms to reduce costs and ensure efficient, safe CCUS implementation.

7.1 Norway: Sleipner and Snøhvit Projects:

Norway is widely recognized for pioneering large-scale offshore CCUS projects. The Sleipner project, operational since 1996, injects approximately 1 million tonnes of CO_2 per year into a saline aquifer beneath the North Sea. The Snøhvit project combines LNG production with CO_2 capture and storage, injecting about 700,000 tonnes per year [65, 66]. Key lessons include:

- **Strong regulatory frameworks**: Norway's CCS legislation, environmental monitoring requirements, and clear liability rules were essential for long-term project success [65].
- **Public engagement and transparency**: Regular reporting, stakeholder involvement, and environmental assessment improved societal acceptance [66].
- **Integration with existing infrastructure**: Utilizing offshore platforms for CO_2 injection reduced capital costs and operational complexity [65].

Libya could benefit from establishing robust regulatory frameworks and public engagement strategies. Offshore fields such as Bouri or new projects like Structures A & E could integrate CO_2 storage into existing platforms to reduce costs and operational challenges.

7.2 United States: Petra Nova and Illinois Basin Projects

The United States has developed several landmark CCUS projects. Petra Nova, located in Texas, captures ~1.6 million tonnes of CO_2 per year from a coal-fired power plant and supplies it for EOR. The Illinois Basin – Decatur Project stores CO_2 in a deep saline formation, demonstrating effective monitoring and verification [67, 68]. Lessons include:

- **Economic incentives and partnerships**: Petra Nova leveraged a combination of tax credits (45Q) and private investment, demonstrating the importance of economic instruments for project viability [67].
- **Monitoring, verification, and modeling**: Advanced reservoir modeling and continuous monitoring at Illinois Basin ensured storage integrity and safety [68].
- **EOR integration as a commercial driver**: Linking storage with enhanced oil recovery increased revenue streams and reduced net costs [67].

Libya can integrate CCUS with EOR in mature oil fields to offset project costs while storing CO_2. Introducing fiscal incentives, such as carbon credits, can attract private sector investment.

7.3 United Arab Emirates: Al Reyadah Project:

The UAE's Al Reyadah project captures CO_2 from a steel plant in Abu Dhabi and injects it for EOR in oil fields, storing ~0.8 million tonnes of CO_2 annually [69]. Key lessons include:

- **Industrial CO_2 utilization**: CCUS can be economically viable when CO_2 is directly used in industrial processes or oil recovery [69].
- **Government-industry collaboration**: Close cooperation between public institutions and private firms enabled rapid project deployment [69].
- **Scalable approach**: Starting with a pilot-scale operation allowed testing, validation, and expansion [69].

Libya could adopt an industrial CO_2 utilization approach, capturing emissions from cement, steel, or gas-processing facilities. Pilot projects can help validate storage sites and demonstrate technical feasibility before scaling up.

7.4 Implications for Libya:

Figure 7 shows the summary of implications for Libya. The global experiences highlight several critical lessons for Libya's CCUS deployment:

1. **Regulatory and Policy Frameworks**: Establish clear legislation, permitting processes, and long-term liability rules [65, 66].
2. **Economic Incentives**: Use carbon credits, tax incentives, and EOR-linked revenues to reduce financial risks [67, 69].

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3. **Technical Expertise and Monitoring**: Develop monitoring, reporting, and verification (MRV) systems for safe CO_2 injection and storage [68].
4. **Public Engagement**: Proactive communication with stakeholders ensures social acceptance and environmental legitimacy [66].
5. **Pilot Projects**: Begin with smaller-scale projects to test technology and infrastructure before full-scale deployment [69].
6. **Integration with Existing Infrastructure**: Leverage Libya's mature oil fields and offshore platforms to reduce capital costs and improve operational efficiency [65, 67].

FIGURE 7: LESSONS FROM INTERNATIONAL CCUS PROJECTS AND IMPLICATIONS FOR LIBYA

TABLE 5: LESSONS FROM INTERNATIONAL CCUS PROJECTS AND IMPLICATIONS FOR LIBYA

Country	Key Lessons	Implications for Libya	References
Norway	Strong regulations, public engagement, use of offshore infrastructure	Set legislation, involve stakeholders, integrate CO_2 storage with existing platforms	[65, 66]
USA	Economic incentives, monitoring, EOR integration	Use fiscal incentives, develop MRV systems, combine CCUS with EOR	[67, 68]
UAE	Industrial CO_2 use, govt-industry collaboration, pilot approach	Capture industrial CO_2, start with pilots, scale gradually	[69]
Overall	Regulatory clarity, incentives, technical expertise, pilot projects	Guide Libya's CCUS deployment using global best practices	[65-69]

VIII. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions:

The figure 9 visually summarizes the four key components that form the overall conclusion of the study. Each component is represented through a dedicated icon and label, arranged vertically for clarity and ease of interpretation

FIGURE 8: IMPLICATIONS FOR LIBYA

- **Current Status**: Libya has significant potential for CCUS deployment, particularly in its mature oil and gas fields such as Bouri, the Sirte Basin, and new offshore projects like Structures A & E [26, 27, 28]. While a few national initiatives aim to reduce flaring and integrate CCUS, overall deployment remains at an early stage, hindered by infrastructure limitations, regulatory gaps, and investment risks.
- **Technological Potential**: Advanced CO_2 capture technologies, digital monitoring, hybrid renewable-CCUS systems, and integration with enhanced oil recovery (EOR) provide viable pathways for large-scale CCUS adoption [53, 54, 55]. Libya's abundant solar resources, existing hydrocarbon infrastructure, and offshore fields offer opportunities for technology integration and cost optimization.
- **Challenges**: Libya faces technical, economic, social, and regulatory challenges. These include insufficient subsurface characterization, high capital costs, limited local technical expertise, weak legal frameworks, and low public awareness.
- **Global Lessons**: Experiences from Norway, the United States, and the UAE highlight the importance of strong regulatory frameworks, economic incentives, stakeholder engagement, pilot

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projects, and integration with existing infrastructure. Libya can adopt similar strategies to accelerate CCUS deployment.

FIGURE 9 : KEY ELEMENTS OF THE STUDY CONCLUSIONS

8.2 Recommendations:

The figure 10 presents a visual summary of the six primary recommendations derived from the study. Each recommendation is represented with a distinct icon and label, organized vertically to enhance readability and ensure a clean, structured layout suitable for presentations or reports.

1. **Policy and Regulatory Framework**: Establish comprehensive CCUS legislation covering permitting, long-term storage liability, environmental monitoring, and safety standards. Align national policies with international climate agreements and carbon market mechanisms.
2. **Infrastructure Development**: Upgrade and expand gas-gathering, processing, and CO_2 transport infrastructure. Utilize existing oil and gas platforms and pipelines for cost-effective CO_2 injection and storage.
3. **Pilot Projects and Research**: Launch small- to medium-scale CCUS demonstration projects in selected oil fields and industrial facilities to test technologies, validate storage sites, and build local expertise.
4. **International Collaboration**: Partner with global energy companies, research institutions, and climate finance bodies to transfer knowledge, share technical risks, and secure funding for CCUS initiatives.
5. **Public Awareness and Capacity Building**: Engage local communities and stakeholders through awareness campaigns and training programs. Develop national technical expertise in CO_2 capture, transport, and storage through university-industry partnerships.
6. **Economic Incentives**: Implement carbon pricing, tax credits, and revenue-sharing mechanisms for CO_2-EOR projects. Encourage participation in carbon credit and emissions trading markets to enhance economic viability.

FIGURE 10 : KEY RECOMMENDATIONS OVERVIEW

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