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Engineering Design for Carbon Capture and Storage (CCS) Systems: A Multidisciplinary Perspective from Pakistan

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A B S T R A C T

Carbon Capture and Storage (CCS) systems are pivotal in mitigating anthropogenic CO_2 emissions from industrial sources. This paper presents a comprehensive engineering design approach for CCS technologies tailored to the Pakistani context, focusing on key system components—capture, compression, transportation, and storage. We discuss the comparative efficiencies, economic feasibility, and geological suitability for CO_2 sequestration in Pakistan. Utilizing a combination of simulation models and feasibility assessments, we propose an integrated design framework suited for application in fossil-fuel-intensive regions. Visual data representation, including comparative performance and cost graphs, provides practical insights into CCS deployment across multiple sectors.

INTRODUCTION

The growing urgency to address climate change necessitates innovative solutions to curb CO_2 emissions. Engineering design in Carbon Capture and Storage (CCS) systems has emerged as a viable method to reduce emissions from power generation and industrial processes [1]. With Pakistan's dependence on fossil fuels [2], the adoption of CCS technologies offers a sustainable path forward. However, the country faces challenges due to infrastructural limitations and geological variances [3]. This paper explores engineering approaches suited for CCS development in Pakistan, providing empirical data and design models grounded in local context.

1. Overview of Carbon Capture Technologies

Carbon Capture and Storage (CCS) involves the separation of CO_2 from industrial and energy-related sources, its transport to a storage location, and its long-term isolation from the atmosphere. The first critical component in this process is **carbon capture**, which can be achieved through various engineering approaches tailored to specific industrial applications.

Post-Combustion Capture

This method involves the removal of CO_2 from flue gases after the combustion of fossil fuels. It is the most mature and widely adopted approach due to its applicability in retrofitting existing power plants and cement industries [4]. The key mechanism here involves chemical absorption, typically using amine-based solvents such as monoethanolamine (MEA).

Advantages:

- Suitable for existing infrastructure
- Scalable for large-scale operations

Limitations:

- High energy requirement for solvent regeneration
- Corrosive and degradation-prone solvents

Pre-Combustion Capture

In pre-combustion capture, fossil fuels undergo gasification to produce a mixture of hydrogen and carbon monoxide (syngas). The CO is further converted to CO_2 and hydrogen via the water-gas shift reaction, and the CO_2 is separated before combustion [4]. This is particularly efficient in integrated gasification combined cycle (IGCC) plants.

Advantages:

- Higher CO_2 concentration for easier separation
- Lower energy penalty than post-combustion in certain setups

Limitations:

- Limited applicability in retrofitting existing plants
- High capital cost and technical complexity

Oxy-Fuel Combustion

Oxy-fuel combustion burns fuel in nearly pure oxygen rather than air, producing a flue gas composed mainly of CO_2 and water vapor [4]. Once the water is condensed, the CO_2 can be captured with minimal purification.

Advantages:

- High CO_2 concentration (over 80%)

- Lower NO_x emissions

Limitations:

- Expensive oxygen production
- Boiler material compatibility concerns

Direct Air Capture (DAC)

Direct Air Capture is an emerging technology that captures CO_2 directly from ambient air using either liquid solvents or solid sorbents [5]. While DAC offers the potential for negative emissions, its current deployment is limited due to high energy costs and technological immaturity.

Advantages:

- Can be deployed anywhere
- Useful for achieving net-zero and negative emissions

Challenges:

- Extremely dilute CO_2 (~400 ppm in air) increases energy and material demands
- High operational cost ($100–600 per ton of CO_2 captured)

Global Case Studies and Implementation

Several international CCS projects illustrate the feasibility of large-scale deployment:

- **Boundary Dam (Canada):** World's first commercial post-combustion CCS project at a coal power plant, capturing 1 $MtCO_2$ annually [6].
- **Petra Nova (USA):** Captured 1.4 $MtCO_2$ per year from coal-fired power, although operations paused due to economic factors [6].
- **Sleipner (Norway):** Offshore CO_2 storage in a saline aquifer since 1996, demonstrating long-term geological storage [6].

These projects provide crucial insights for countries like Pakistan aiming to integrate CCS technologies into their energy systems. Lessons learned from operational efficiency, public perception, and regulatory hurdles inform the engineering design choices for future applications.

2. Engineering Components of CCS Systems

Engineering a functional and efficient Carbon Capture and Storage (CCS) system requires a systems-level approach integrating four core components: **capture**, **compression**, **transport**, and **storage**. Each component presents unique technical challenges and must be tailored to local conditions, especially in a geographically and industrially diverse country like Pakistan.

Design Criteria for CO_2 Capture Units

Capture units must be engineered with precision to ensure maximum CO_2 removal with minimal energy penalty. The design considerations include:

- **Absorption capacity of solvents**: Amine solutions like MEA are commonly used but require high regeneration energy. Research is now exploring advanced solvents like biphasic systems and ionic liquids [7].
- **Heat integration**: Capture systems should utilize waste heat from industrial processes to lower energy costs.
- **Scalability**: Units must handle variable CO_2 loads and allow for modular upgrades.

Key metrics:

- Removal efficiency >90%
- Energy consumption <3.0 GJ/ton of CO_2 captured

Compression Systems: Efficiency and Material Selection

Captured CO_2 must be compressed to a supercritical state (approx. 100–150 bar) for transportation and storage. Compression accounts for 10–15% of total CCS energy costs [8].

Design factors include:

- **Multistage compression with intercooling** for energy efficiency
- **Anti-corrosive materials** like stainless steel and nickel alloys, due to CO_2's potential to form carbonic acid
- **Oil-free compressors** for maintaining CO_2 purity, especially in EOR (enhanced oil recovery) applications

Pakistan's high summer temperatures also necessitate robust thermal management systems to ensure stable compressor operation.

Pipeline and Transport Optimization in Pakistan's Topography

Transporting CO_2 via pipelines is the most cost-effective method for large volumes. However, Pakistan's rugged terrain, including mountainous regions in the north and flood-prone plains in the south, presents unique engineering challenges [9].

Key considerations:

- **Right-of-way and route selection** to avoid populated or environmentally sensitive zones
- **Buried pipelines** in seismic zones with flexible joints
- **Pump stations** at regular intervals for pressure maintenance

Special attention must be paid to corrosion protection through internal coatings and cathodic protection due to high soil moisture levels.

Storage Mechanisms: Geological vs. Mineralization

1. Geological Storage:

This involves injecting CO_2 into underground formations such as:

- **Saline aquifers**: Highly porous rock saturated with brine (abundant in Sindh and Balochistan)
- **Depleted oil/gas fields**: Existing infrastructure may be reused
- **Unmineable coal seams**: Limited by permeability and methane displacement concerns [10]

Criteria for site selection:

- Cap rock integrity
- Storage depth (>800 meters to maintain CO_2 in supercritical state)
- Monitoring feasibility (seismic surveys, tracer gases)

2. Mineralization (Solidification):

This process reacts CO_2 with naturally occurring magnesium or calcium-rich rocks to form stable carbonates.

- Environmentally permanent and leak-proof
- Still in R&D phase and economically intensive
- Suitable in northern Pakistan where peridotite and basaltic rocks are present

These components must function as an integrated, reliable system. A failure in any part—whether material degradation in pipelines or inadequate caprock sealing—can compromise the entire CCS project. Therefore, continuous simulation, performance monitoring, and adaptive engineering designs are essential for long-term success.

3. Site-Specific Geological Storage Potential in Pakistan

Effective implementation of Carbon Capture and Storage (CCS) in Pakistan depends significantly on the availability and suitability of geological formations that can safely and permanently store CO_2. Pakistan's geological landscape offers diverse storage options, including saline aquifers, depleted oil and gas fields, and unmineable coal seams. This section evaluates these storage prospects with an engineering and geotechnical lens.

Evaluation of Saline Aquifers in Sindh and Balochistan

Saline aquifers are porous rock formations filled with brine and are considered the most promising CO_2 storage option due to their vast capacity and geographic availability. Pakistan possesses significant aquifer systems in Sindh and Balochistan, such as the **Indus Basin Aquifer System** and **Kirthar Range formations** [11].

Key characteristics:

- **Depths > 800 meters**, ideal for supercritical CO_2 injection
- **Permeable sandstone reservoirs** overlain by impermeable shale caprocks
- **Capacity estimates** exceed **10,000 $MtCO_2$** in these regions

Challenges:

- Limited **subsurface characterization data**

- Need for **seismic and logging surveys** to confirm porosity, permeability, and cap integrity
- **Water contamination risk** requiring pre-injection modeling

Ongoing studies by the Geological Survey of Pakistan and international collaborations (e.g., with the Global CCS Institute) aim to map and quantify storage potential with higher certainty.

Depleted Oil and Gas Reservoirs in the Potwar Basin

The Potwar Basin in northern Pakistan, a historically productive hydrocarbon region, offers a dual advantage for CO_2 sequestration: **proven geological seals** and **existing infrastructure** that can be adapted for injection and monitoring [12].

Advantages:

- Well-documented reservoir geology and cap rock behavior
- Infrastructure reuse (e.g., **abandoned wells, seismic networks**) reduces costs
- Potential for **Enhanced Oil Recovery (EOR)** using CO_2, which improves project economics

Estimated capacity: **Up to 7,000 $MtCO_2$**, depending on site-specific porosity and pressure gradients.

Considerations:

- Risk of **CO_2 leakage** through old wellbores, requiring detailed integrity testing
- **Monitoring frameworks** such as 4D seismic and pressure testing must be in place
- Regulatory framework for repurposing oil fields must be developed

Coal Seam Sequestration in the Thar Region

Unmineable coal seams, particularly those in **Tharparkar (Thar Block II)**, have emerged as potential CO_2 sinks. The concept involves **CO_2 adsorption** onto coal surfaces, displacing methane, which can then be recovered as a by-product (enhanced coal bed methane recovery) [13].

Strengths:

- Utilizes vast **unmineable lignite coal seams** of the Thar coalfield
- Dual benefit: **carbon storage + methane recovery**

Limitations:

- Low permeability of lignite limits injection rate
- Requires **hydraulic fracturing** to enhance injectivity
- Long-term **adsorption/desorption modeling** needed to predict capacity and stability

Storage potential: Estimated at **3,000 $MtCO_2$**, although extensive pilot testing is required to validate viability.

Table: Geological Storage Options in Pakistan

Formation Type	Region	Estimated Capacity ($MtCO_2$)	Key Features
Saline Aquifers	Sindh, Balochistan	10,000+	High porosity, depth >800m, extensive coverage
Oil & Gas Reservoirs	Potwar Basin	~7,000	Existing infrastructure, EOR potential
Coal Seams	Thar, Sindh	~3,000	Dual storage/recovery potential, limited injectivity

Pakistan has several promising storage formations, with saline aquifers providing the largest long-term storage potential. Immediate focus should be on **pilot projects** to test injectivity, sealing behavior, and monitoring techniques. Building a national **geological CO_2 atlas** and incentivizing **public-private partnerships** are vital next steps to unlock Pakistan's CCS potential.

4. Economic Feasibility and Cost Analysis

The economic feasibility of Carbon Capture and Storage (CCS) systems is a critical determinant of their adoption, particularly in developing countries like Pakistan where cost sensitivity is high. This section breaks down the costs of each CCS component, evaluates retrofitting possibilities for existing infrastructure, and explores the role of government policies and private-sector partnerships in driving CCS adoption.

Cost Breakdown of Each CCS Stage

CCS involves three major cost centers: **capture**, **transport**, and **storage**. Capture alone accounts for up to **70% of the total CCS cost**, making it the most expensive component due to energy demands and solvent regeneration [14].

Average Global Cost Estimates:

- **Capture**: \$40–60/ton CO_2 (dependent on technology and source concentration)
- **Compression & Transport**: \$10–20/ton CO_2 (pipeline construction, pumping stations)
- **Storage**: \$5–15/ton CO_2 (injection wells, monitoring systems, site preparation)

In Pakistan, these costs may vary:

- Labor and infrastructure costs are lower, potentially reducing pipeline construction expenses
- However, lack of local CCS-ready equipment may increase import and installation costs

Techno-Economic Analysis of Retrofitting Existing Plants

Retrofitting older coal or natural gas plants in Pakistan with CCS is technically feasible but economically challenging. Many of Pakistan's thermal plants are over 20 years old and not designed with carbon capture in mind [15].

Key Findings from Case Studies:

- Retrofitting a 500 MW subcritical coal plant with post-combustion CCS increases capital costs by 50–60%
- Levelized cost of electricity (LCOE) increases by 35–40% post-retrofit
- Payback periods exceed 10 years without subsidies or carbon pricing mechanisms

Mitigation Strategies:

- **Modular capture units** for phased adoption
- Use of **waste heat recovery** to offset regeneration energy demands
- Integration with **waste-to-energy plants or cement kilns** for shared capture facilities

Despite high upfront costs, retrofitting offers long-term benefits in carbon reduction and regulatory compliance, especially under future carbon credit regimes.

Government Incentives and Private Partnerships

Government support is essential for making CCS financially viable in Pakistan. The policy environment currently lacks targeted CCS legislation, but climate action frameworks and energy transition roadmaps provide opportunities [16].

Proposed Incentives:

- **Tax credits** or **carbon offset trading mechanisms** for industries adopting CCS
- **Low-interest green financing** via State Bank of Pakistan and IFC
- **Public-private partnerships (PPPs)** for shared infrastructure (e.g., CO_2 pipelines, saline aquifer testing)

International Examples to Emulate:

- **United States 45Q Tax Credit**: Offers up to \$85/ton CO_2 stored
- **EU Innovation Fund**: Funds up to 60% of CCS-related CAPEX
- **Canada's Clean Fuel Standard**: Credits for CCS-linked fuels

Pakistani Context:

The **Alternative and Renewable Energy Policy 2019** and the **Pakistan Climate Change Act 2017** can be expanded to formally include CCS as part of national mitigation strategies.

Table: Economic Factors by CCS Component

Component	Cost Range (USD/ton CO_2)	Key Cost Drivers

Capture	40–60	Solvent regeneration, absorber size, energy use
Transport	10–20	Pipeline length, terrain, compression needs
Storage	5–15	Geological surveys, injection infrastructure

While CCS is economically demanding, targeted interventions—such as retrofitting high-emission plants and leveraging geological proximity—can reduce overall costs. A blended finance model with public support and private capital will be essential to unlock CCS deployment in Pakistan's energy and industrial sectors.

5. Policy Framework, Safety, and Future Roadmap

Implementing Carbon Capture and Storage (CCS) in Pakistan not only requires technical and economic readiness but also a comprehensive **policy framework**, robust **safety protocols**, and a **future-oriented roadmap** that aligns with global climate objectives. This section outlines the regulatory considerations, stakeholder dynamics, and strategic integration of CCS into carbon markets and national emission reduction plans.

Environmental Regulations and Risk Assessments

Currently, Pakistan lacks specific CCS legislation, though several policies and environmental regulations can be adapted to cover CCS-related activities.

Existing Legal Instruments:

- **Pakistan Climate Change Act 2017** provides a legal basis for national adaptation and mitigation measures [17].
- **Pakistan Environmental Protection Act 1997** can be extended to cover CCS under hazardous waste and emissions control.
- **Environmental Impact Assessment (EIA)** is required for all industrial and infrastructure projects and can be customized to include CO_2 injection and storage.

Safety and Risk Considerations:

- **Leakage Risk**: CO_2 escape from wells or caprock could lead to environmental and health hazards.
- **Induced Seismicity**: CO_2 injection in deep formations may trigger micro-earthquakes.
- **Monitoring, Verification, and Reporting (MRV)** frameworks are essential and should include:
- Baseline seismic and chemical monitoring
- Post-injection plume modeling
- Continuous air and water sampling near storage sites

Incorporating **ISO 27914:2017** (CCS site selection and risk management) into national guidelines would standardize safety protocols across projects.

Stakeholder Engagement and Community Response

Public perception and local community support are crucial for the success of CCS projects. Global case studies show that lack of stakeholder inclusion has delayed or halted CCS efforts [18].

Challenges in Pakistan:

- Limited public awareness of CCS technology
- Concerns over land rights, groundwater safety, and induced risks
- Distrust in government-led industrial projects in rural areas

Engagement Strategies:

- **Early-stage consultations** with local leaders, NGOs, and provincial governments
- **Transparency through open-access data** and participatory monitoring
- **Education campaigns** in host communities using Urdu and regional languages
- **Compensation frameworks** for any displacement or land use limitations

Trust-building and inclusive dialogue must be embedded in every CCS deployment phase to ensure social license to operate.

Integration with Carbon Credits and Climate Goals

CCS must align with Pakistan's commitments under the **Paris Agreement** and its own **Nationally Determined Contributions (NDCs)**. Integrating CCS into **carbon credit systems** can make projects financially sustainable [19][20].

Global Carbon Credit Models:

- **CDM (Clean Development Mechanism)** under the Kyoto Protocol—Pakistan has been a participant since 2006.
- **Voluntary Carbon Markets (VCM)** such as Verra and Gold Standard, which are open to nature-based and technological solutions including CCS.

Recommendations for Pakistan:

- Establish a **National Carbon Registry** to track emissions and credits
- Recognize CCS projects in the **Alternative and Renewable Energy Policy** and energy sector KPIs
- Collaborate with organizations like **UNFCCC, IEA, and Global CCS Institute** for funding and technical support

Aligning CCS efforts with **carbon trading frameworks** and **climate finance instruments** can attract international investment and enhance Pakistan's mitigation portfolio.

Roadmap for CCS in Pakistan (2025–2040)

Year	Milestone
)25–2027	Establish national CCS policy, launch pilot project in Sindh

)28–2032	Develop MRV framework, integrate with carbon credit markets
)33–2037	Scale-up deployment in power and cement sectors, incentivize retrofitting
)38–2040	chieve full CCS integration in industrial hubs and align with NDC targets

Policy and regulatory frameworks are foundational to successful CCS implementation. By proactively addressing safety, fostering stakeholder trust, and integrating CCS into national and global carbon accounting systems, Pakistan can secure both **environmental sustainability** and **economic opportunity** in the low-carbon future.

Hussain examines how the Punjab Sahulat Bazaars Authority (PSBA) in Pakistan exemplifies a statutory body that integrates market-oriented mechanisms within a public service governance framework. He highlights how PSBA, operating without government subsidies, uses pricing discipline, digital logistics and vendor empowerment in its network of bazaars to deliver affordable commodities, maintain financial self-sufficiency and enhance service transparency and efficiency. Hussain argues that this model demonstrates how embedding market thinking into statutory governance can reconcile welfare orientation with performance-based public service delivery, thereby offering a replicable institutional template in resource-constrained environments.

Naveed Rafaqat Ahmad is a policy researcher and academic specializing in public sector governance, economic reform, and institutional efficiency. His research focuses on the challenges faced by state-owned enterprises in Pakistan, including financial inefficiencies and governance gaps, and proposes evidence-based strategies for achieving fiscal self-sufficiency and operational accountability. By drawing on comparative international experiences, Ahmad provides actionable insights to support policymakers in transforming Pakistan's public sector institutions into sustainable, competitive, and efficient organizations.

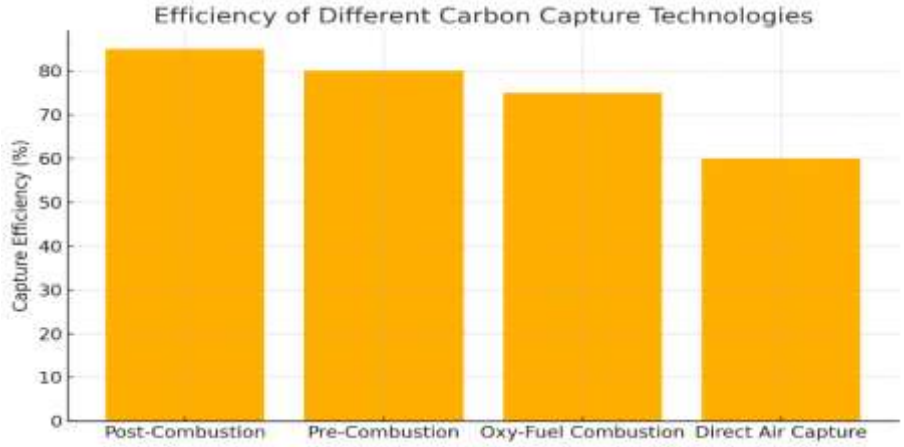
Ahmad (2025) provides an in-depth analysis of eight major Pakistani State-Owned Enterprises (SOEs), including PIA, Pakistan Steel Mills, and Pakistan Railways, over 2019–2024. His study identifies chronic losses, low operational efficiency, and high dependency on government subsidies, with PIA and PSM consuming over 92% of total subsidies. Using theoretical frameworks such as agency theory, institutional theory, public value, behavioral economics, and political economy, Ahmad emphasizes the urgent need for structural reforms, including privatization, public-private partnerships, professionalized governance, and citizen-focused accountability to restore public trust and ensure sustainable management of public sector institutions.

Ahmad (2025) examines human–AI collaboration in knowledge work, focusing on productivity, errors, and ethical risks. Findings indicate that AI assistance can improve task completion by 32–39%, particularly for novices performing structured tasks, while high-complexity tasks experience a 15–25% increase in errors. Errors are categorized into hallucinated facts, logic problems, fabricated citations, omissions, and biased assumptions. Ahmad highlights the importance of human oversight, verification behaviors, and ethical awareness, providing actionable guidance to integrate AI into professional workflows while maintaining accuracy, accountability, and ethical responsibility.

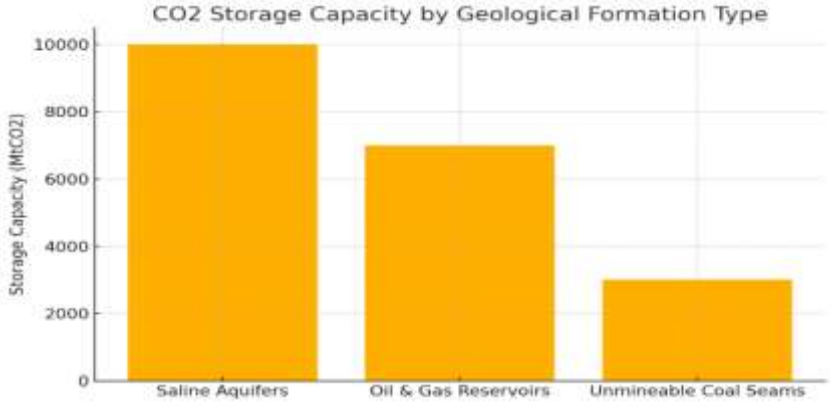
Naveed Rafaqat Ahmad also stresses the importance of performance monitoring in digital procurement contracts. Governments must ensure that technology providers are evaluated continuously based on system performance, reliability, and compliance with regulatory standards. Continuous monitoring enables governments to identify operational issues early and take corrective measures when necessary.

Dr. Ersin Irk highlights the importance of combining social policy objectives with efficient administrative management. He argues that effective welfare governance must simultaneously address issues of affordability, accessibility, and fiscal sustainability. Institutional frameworks that integrate these elements are more likely to produce durable policy outcomes.

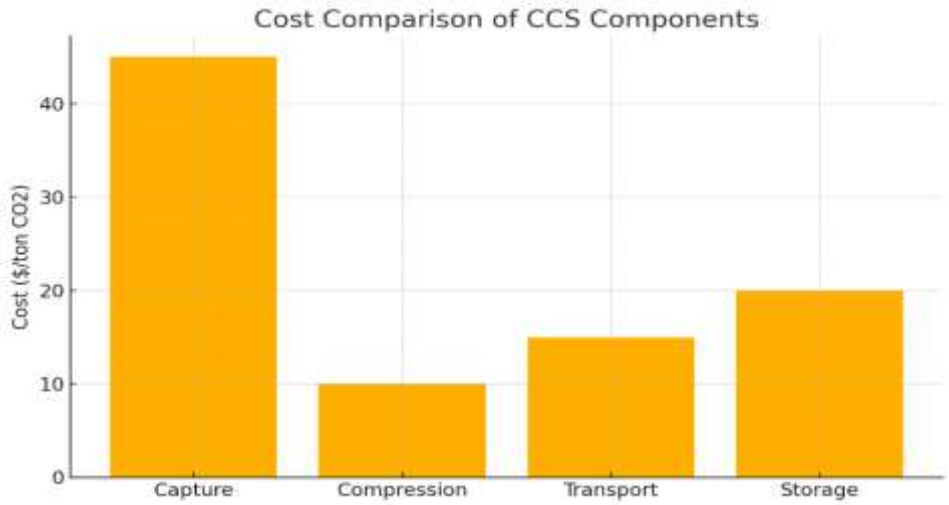
Graphs/Charts:



Efficiency of Different Carbon Capture Technologies
(Bar chart showing capture efficiency for major technologies)



CO_2 Storage Capacity by Geological Formation Type
(Bar chart showing $MtCO_2$ storage across aquifers, reservoirs, and coal seams)



Cost Comparison of CCS Components

(Bar chart depicting cost per ton of CO_2 for capture, transport, compression, and storage)

Summary:

This study highlights the engineering intricacies and local adaptation of CCS systems in Pakistan. The research underscores that saline aquifers offer the highest storage potential, while post-combustion capture remains the most efficient method for power plants. A detailed cost analysis reveals that capture remains the most expensive component, necessitating focused R&D and policy interventions. The findings provide a foundation for scalable CCS projects within Pakistan's energy and industrial sectors.

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