

Economic Viability of Carbon Capture and Storage: - Financial and Economic Management Perspective

Author :- Arindam Mukherjee

Institution :- University of energy and petroleum studies

Abstract :- Carbon Capture and Storage (CCS) is a key technology for reducing greenhouse gas emissions from industrial and energy sectors. However, its large-scale deployment depends not only on technical feasibility but also on economic and financial viability. This study examines CCS from a financial and economic management perspective by analysing capital expenditure, operational costs, revenue mechanisms, carbon pricing incentives, and risk factors. Key economic evaluation tools such as Net Present Value (NPV), Internal Rate of Return (IRR), and levelized cost of CO₂ capture are discussed to assess project feasibility. The analysis highlights that CCS becomes economically attractive under strong carbon pricing policies, government incentives, and revenue generation through carbon credits or enhanced oil recovery. Effective financial planning and policy support are essential for commercial deployment and long-term sustainability of CCS projects.

Keywords: - Carbon Capture and Storage (CCS); Economic Viability; Financial Analysis; Capital Expenditure (CAPEX); Operational Expenditure (OPEX); Net Present Value (NPV); Internal Rate of Return (IRR); Carbon Pricing; Risk Assessment; Energy Economics; Policy Incentives; Levelized Cost of CO₂ Capture.

Introduction: Carbon Sequestration involves capturing CO₂ emissions, transporting and storing them in underground geological formations like depleted oil fields or saline aquifers. There are generally three methods of capture, which are primarily pre-combustion, post-combustion, and oxyfuel Combustion. Pre-combustion capture involves converting fuel into syngas (CO+H₂) and then separating CO₂ from H₂ for sequestration, which has been efficient for gasification processes, that involves in converting fossil fuels or biomass into syngas (CO+H₂) at high temperature with limited oxygen. Post-Combustion capture involves capturing CO₂ from flue gases after fossil fuel combustion. Common tech generally includes amine scrubbing, which generally uses solvents to absorb Carbon -Di-Oxide and it is suitable for retrofitting existing power plants. India's large coal-based power sector could leverage this. Oxy fuel combustion burns the fuels in pure oxygen, producing CO₂ and water vapour, making carbon dioxide capture easier. India's steel and cement industries could benefit from this process. Generally, Carbon Capture involves 3 Steps: -

- A) Capture carbon dioxide from emission sources.
- B) Transport it to storage sites.
- C) Store it in underground (Geological sequestration)

As we previously described Carbon-Di-Oxide sequestration involves 3 steps, which have been broadly described below: -

A) Capture: - Carbon Di-Oxide has been separated from emissions using technologies like amine scrubbing or membranes, in which they use a liquid amine, which is an organic compound derived from ammonia (NH₃) by replacing hydrogen with organic groups. In CO₂ capture, amines like MEA (monoethanolamine) are used to absorb CO₂ from gases. MEA reacts with CO₂ in fuel gases to form a carbamate compound, and then the Carbon di oxide rich MEA is heated or regenerated to release CO₂, and MEA is reused. This process is generally efficient to produce MEA, but it is energy-intensive.

B) Transport: Carbon -dioxide has been compressed to make it easier to transport and store. Typically, it's compressed to a supercritical state like a dense liquid at high pressure (70-80 Bar) and then it has been transported via pipelines (Most common for large volumes) or via pipe lines (Most common for large volumes) or ships for smaller volumes. Pipeline materials are usually carbon steel or corrosion-resistant alloys. Safety measures include monitoring for leaks, pressure control, and corrosion protection. Regular inspections and maintenance are the key.

C) Storage: - Carbon Di-Oxide has been injected into geological formations like depleted oil fields or saline aquifers. CO₂ storage involves injecting it into geological formations like

i) Depleted oil and gas fields

ii) Saline aquifers

iii) Basalt formations

The Carbon dioxide trapped by physical and chemical mechanisms, monitoring ensures containment and detects any leaks. Site selection generally involves for evaluating; i) Storage capacity, ii) Injectivity (How easily CO₂ can be injected), iii) Containment (Seal integrity), iv) Risks of leakage or seismic activity.

Monitoring Tech generally includes: - I) Seismic Survey, II) Pressure sensors, III) Satellite monitoring.

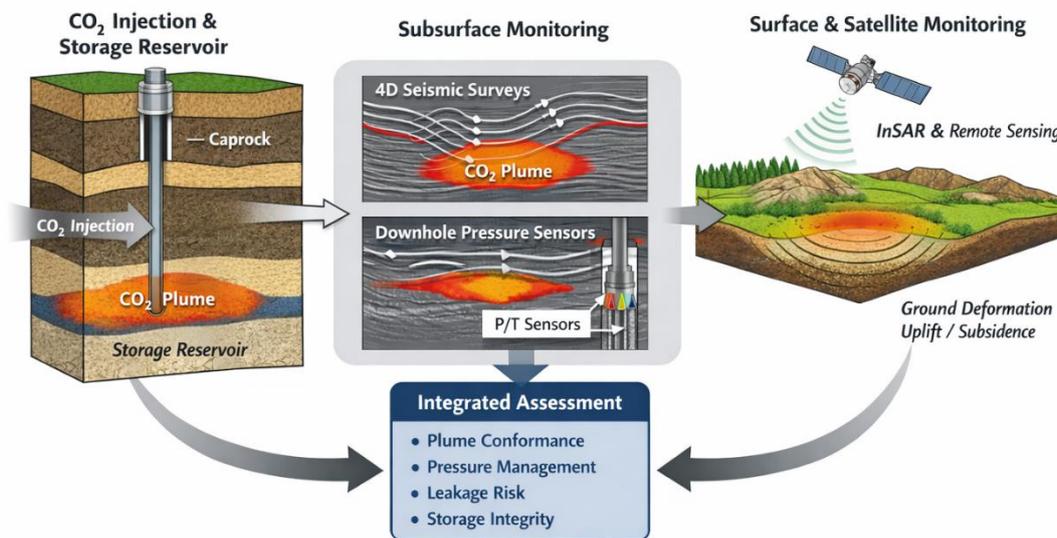


Figure 1. Single-panel workflow of integrated monitoring technologies for carbon sequestration.

CO₂ Injection into a deep storage reservoir is monitored using time-lapse seismic surveys to image plume migration and elastic property changes, downhole pressure sensors to track reservoir pressure evolution and caprock integrity, and satellite-based monitoring to detect surface deformation. Integration of subsurface and surface datasets enables continuous assessment of storage performance, containment security, and long-term storage integrity.

Fig 1: Single-panel workflow of integrated monitoring technologies for carbon sequestration. CO₂ injection into a deep storage reservoir is monitored using time-lapse seismic surveys to image plume migration and changes in elastic properties, downhole pressure sensors to track reservoir pressure evolution and caprock integrity, and satellite-based monitoring to detect surface deformation. The integration of subsurface and surface datasets enables the continuous assessment of storage performance, containment security, and long-term integrity.

Now, for all these, we can understand that money is an important deciding factor for the CCS project.

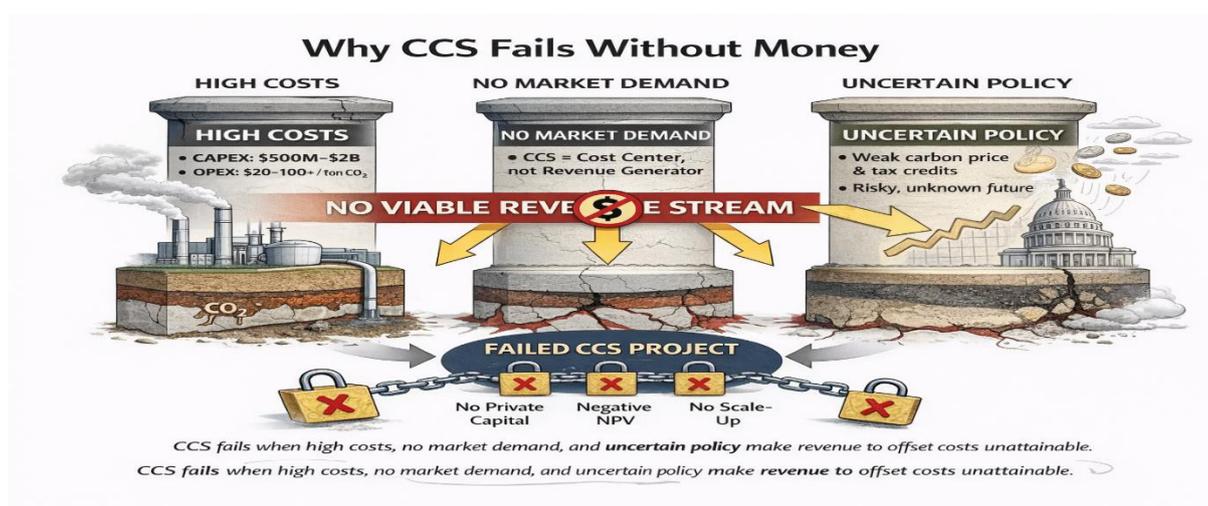


Fig2:-Why CCS fails without money.

Carbon Capture and Storage (CCS) projects face failure when high capital and operational costs, lack of market demand for CO₂ storage, and uncertain policy frameworks combine to eliminate viable revenue streams. These financial challenges result in negative net present value (NPV), a lack of private investment, and an inability to scale up, ultimately leading to unprofitable or abandoned CCS projects.

Methodology: - In the “Carbon sequestration” project, we generally deal with two types of cost, which are mainly microeconomics and macroeconomics, especially for CCS vs CO₂-EOR work. Carbon capture and storage (CCS) often fails in the absence of adequate financial support because, at the project (microeconomic) level, the cost structure overwhelmingly exceeds available revenue streams. High capture costs, coupled with additional expenses for CO₂ transport, injection, long-term monitoring, and liability management, create a heavy financial burden for operators. On the revenue side, income from carbon pricing or credits is frequently too low or too volatile, tax incentives are either insufficient or uncertain, and CO₂-EOR revenues depend strongly on oil prices and do not reliably close the economic gap. As a result, total revenues remain below the break-even threshold, leading to negative cash flow and project losses. Without strong carbon pricing, stable incentives, or public financial support to internalise the societal value of emissions reduction, CCS remains economically unattractive for private investors despite its clear macroeconomic and climate benefits.

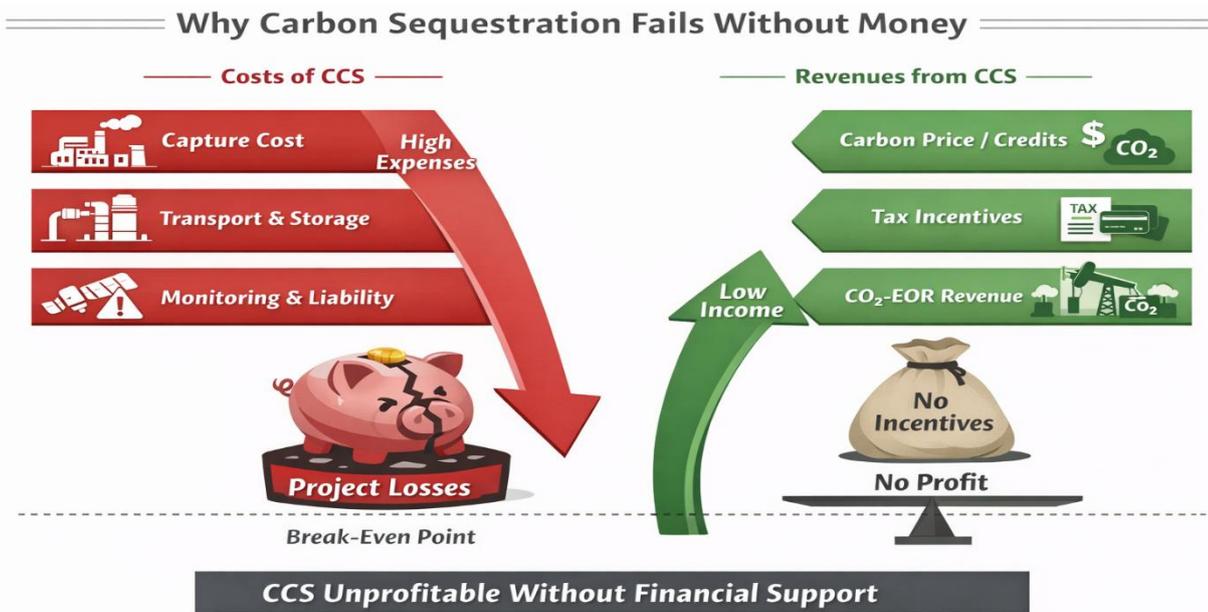


Fig 3: -Why carbon capture and storage (CCS) fails without adequate financial support in developing economies. The diagram contrasts high project-level costs—dominated by CO₂ capture, transport, storage, monitoring, and long-term liability—with limited and uncertain revenue streams from carbon pricing, incentives, and CO₂-EOR. In regions such as India, Africa, and the Middle East, weak carbon markets, low policy support, and price volatility prevent projects from reaching the break-even point, resulting in negative cash flow despite the broader macroeconomic and climate benefits of CCS.

In developing economies such as **India, many African countries, and parts of the Middle East**, carbon capture and storage (CCS) fails primarily because the microeconomic costs are high while the enabling financial and policy frameworks remain weak or fragmented. Capture costs are elevated due to ageing power plants, energy-intensive industrial facilities, and limited access to low-cost capital, while additional expenses for CO₂ transport infrastructure, site characterisation, monitoring, and long-term liability place further strain on project economics. On the revenue side, carbon prices are often absent or very low, domestic carbon markets are immature or non-existent, and public subsidies or tax credits for CCS are limited compared to developed economies. CO₂-EOR can improve project economics in oil-producing regions of the Middle East and parts of Africa, but revenues remain highly sensitive to oil price volatility and do not guarantee net emissions reductions. As a result, CCS projects struggle to reach the break-even point and are unattractive to private investors. Without international climate finance, public-private partnerships, shared transport and storage hubs, and policies that recognise CCS as a strategic decarbonization tool for hard-to-abate sectors, CCS remains economically unviable at the project level despite its significant macroeconomic benefits for energy security, industrial development, and long-term climate risk reduction in developing regions.

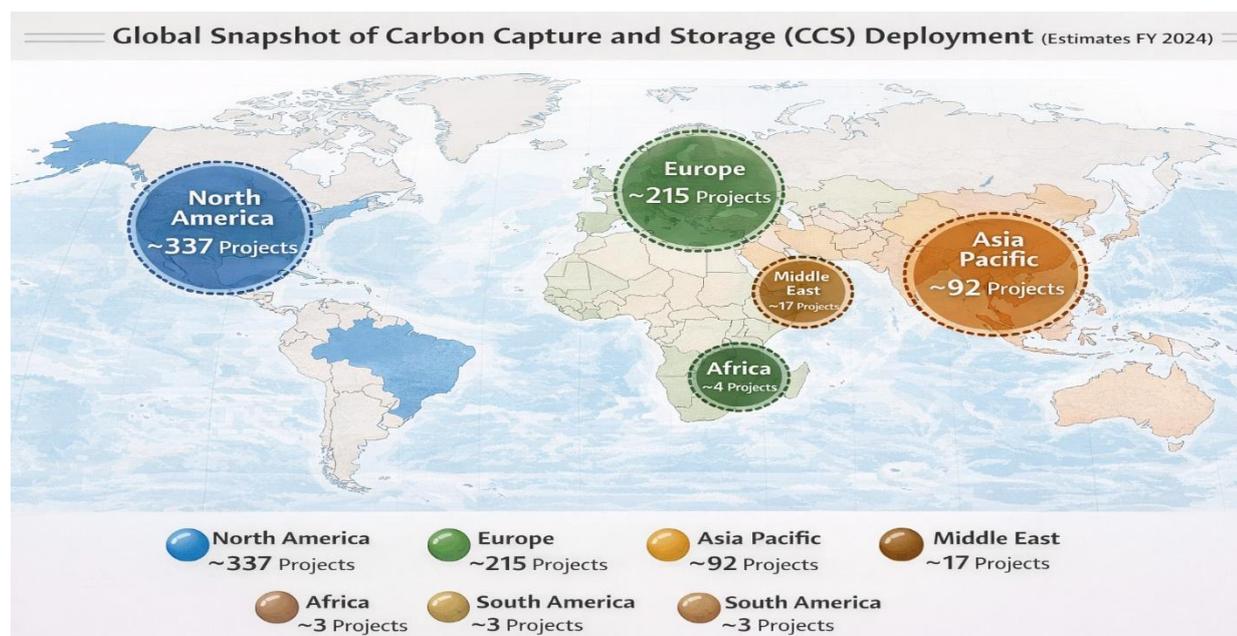


Fig 4 :-Global distribution of carbon capture and storage (CCS) projects by region

Table 1. Microeconomics of Carbon Sequestration (Project / Firm Level)

Category	Component	Description / Economic Implication
Costs (Micro)	CO ₂ capture cost	Largest cost component: high energy penalty for power plants
	Industrial capture	Cement, steel, and refineries are harder to decarbonise → higher capture cost
	Transport cost	Pipelines (high upfront CAPEX) vs shipping (flexible but limited)
	Distance to storage	A longer distance significantly increases the total cost
	Injection cost	Drilling and completion of CO ₂ injection wells
	Monitoring cost	Seismic surveys, pressure monitoring, satellite surveillance
	Long-term liability	Site closure, post-injection monitoring, and leakage responsibility
	Typical total cost	USD 40–120 per ton CO₂ (often higher)
Revenues (Micro)	Carbon price/credits	Income from carbon markets or offset schemes
	Tax incentives	Government support (e.g., 45Q-type credits)
	CO ₂ -EOR revenue	Incremental oil production offsets CCS cost
	Compliance value	Avoided carbon taxes or regulatory penalties
Decision Metrics	NPV	Measures project profitability over life
	IRR	Investor return benchmark
	Break-even carbon price	Minimum CO ₂ price needed for viability
	Sensitivity factors	Carbon price volatility, oil price (CO ₂ -EOR), monitoring & liability cost
Key Insight	—	<i>Without strong carbon pricing or incentives, standalone CCS usually fails financially</i>

Table 2. Macroeconomics of Carbon Sequestration (Economy / Policy Level)

Aspect	Description
Climate externality	CO ₂ emissions are a negative externality not priced by markets
Market failure	Climate damages are undervalued
Social value of CCS	Emissions reduction benefits society more than the private investor
Macroeconomic benefits	Reduced climate-related economic losses
	Energy system stability (firm low-carbon power)
	Job creation in pipelines, subsurface operations, monitoring, and regulation
	Industrial competitiveness for cement, steel, and refining
Policy instruments	Carbon tax or Emissions Trading System (ETS)
	CCS subsidies and tax credits
	Contracts for Difference (CfD)
	Public funding for CO ₂ transport hubs and shared storage
	Long-term liability transfer to the state
Trade-offs	High upfront public expenditure
	Opportunity cost relative to renewables
	The risk of CCS delaying the energy transition if poorly governed
Key Insight	<i>CCS is often privately inefficient but socially efficient</i>

Table 3. Micro–Macro Link: Why CCS Needs Policy Support

Aspect	Microeconomic View	Macroeconomic View
Carbon price	Too low or volatile	Must reflect the social cost of carbon
Risk	Concentrated on investors	Spread across society
Time horizon	10–20 years	50–100 years of climate benefit
Monitoring cost	Operator burden	Public good (safety, trust)
CO ₂ -EOR	Revenue opportunity	Risk of additional fossil production

Table 4. CCS vs CO₂-EOR: Economic Contrast

Aspect	CO ₂ -EOR	Dedicated CCS
Microeconomics	✓ Profitable at moderate oil prices	✗ Often unprofitable alone
Revenue driver	Incremental oil production	Carbon price/incentives
Macroeconomics	△ Climate benefit depends on lifecycle emissions	✓ Strong climate justification
Policy reliance	Moderate	High

Carbon sequestration fails at the microeconomic level without incentives, but succeeds at the macroeconomic level when climate externalities are properly priced.

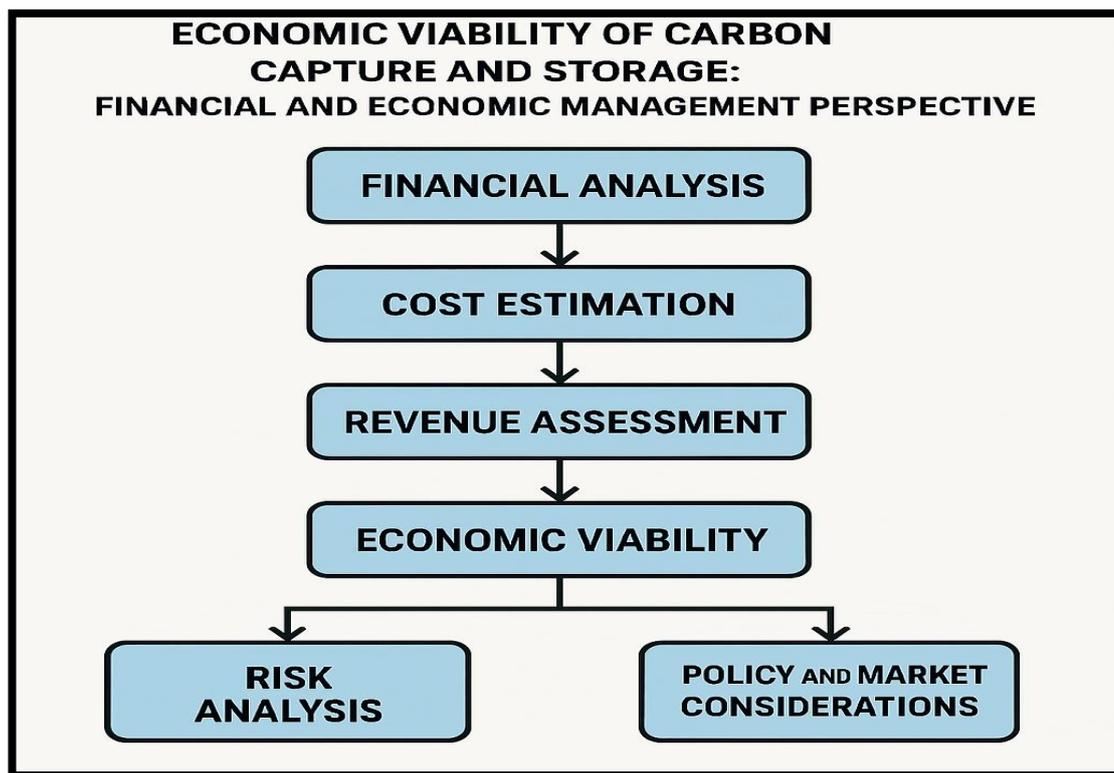


Fig 5 :-Flowchart illustrating the methodology for evaluating the economic viability of Carbon Capture and Storage (CCS) from a financial and economic management perspective. The diagram outlines key stages, including investment and operational costs, revenue sources, cost-benefit analysis, risk assessment, financial modelling, and policy alignment, culminating in a viability decision.

A) Financial analysis: - The financial analysis evaluates the economic feasibility of Carbon Capture and Storage (CCS) projects by quantifying profitability, investment efficiency, and cost performance under different carbon pricing and policy scenarios.

Cost Data for Carbon Capture and Storage (CCS) — Published Literature Summary (Table 5)

Cost Component	Application / Context	Cost Range (USD per ton CO ₂)	Key References / Source
Capture Cost	Natural gas processing / High purity streams	\$15 – \$25	Literature reviews, industry case studies
	Industrial facilities (ammonia, ethanol)	\$22 – \$36	Technical cost assessments
	Coal power / Heavy industry	\$20 – \$150+	Academic & policy reports
	Complex industrial sources	<\$50 to >\$500	Specialised case studies
Transport Cost	Onshore pipeline (large scale)	\$4 – \$45	Transport cost modelling studies
	Pipeline (≈250 km scenario)	\$1.3 – \$15.3	Infrastructure-based economic analysis
Storage Cost	Geological / Saline storage	\$2 – \$15	Storage cost assessment reports
	Broader storage estimates	\$20 – \$80	Global storage cost literature
Full Chain CCS	Low-end integrated project	~\$60 – \$100	Market & industry projections
	Typical current projects	\$100 – \$250	International project data
	European industrial cases	~ \$198	Policy & investment reports
	Global range	\$70 – \$250+	Multi-region assessment studies

CCS Cost Structure – Oil Refinery (1 million tCO₂/year)

Cost Component	Cost Range (USD/tCO ₂)	Selected Medium Value (USD/tCO ₂)	Annual Cost (USD Million)	Source (Published Literature)
CO ₂ Capture	30 – 90	50	50	International Energy Agency (IEA CCS Reports); Global CCS Institute Global Status Reports; Rubin et al., 2015
CO ₂ Transport (Pipeline)	5 – 20	12	12	Global CCS Institute; Smith et al., 2021 (IJGHG)
CO ₂ Storage (Geological/EOR)	10 – 30	18	18	International Energy Agency; Global CCS Institute
Total CCS Cost	60 – 140	80	80 million / Year	Aggregated from the above sources

Here is your 20-Year Cash Flow Table based on the following assumptions:

- **Industry:** Oil Refinery
- **CO₂ Captured:** 1 Mt/year
- **Carbon Price:** \$100/ton
- **Total CCS Cost:** \$80/ton
- **Annual Net Cash Flow:** \$20 million
- **Project Lifetime:** 20 years
- **Discount Rate:** 10%
- **Initial Investment (CAPEX assumed):** \$600 million

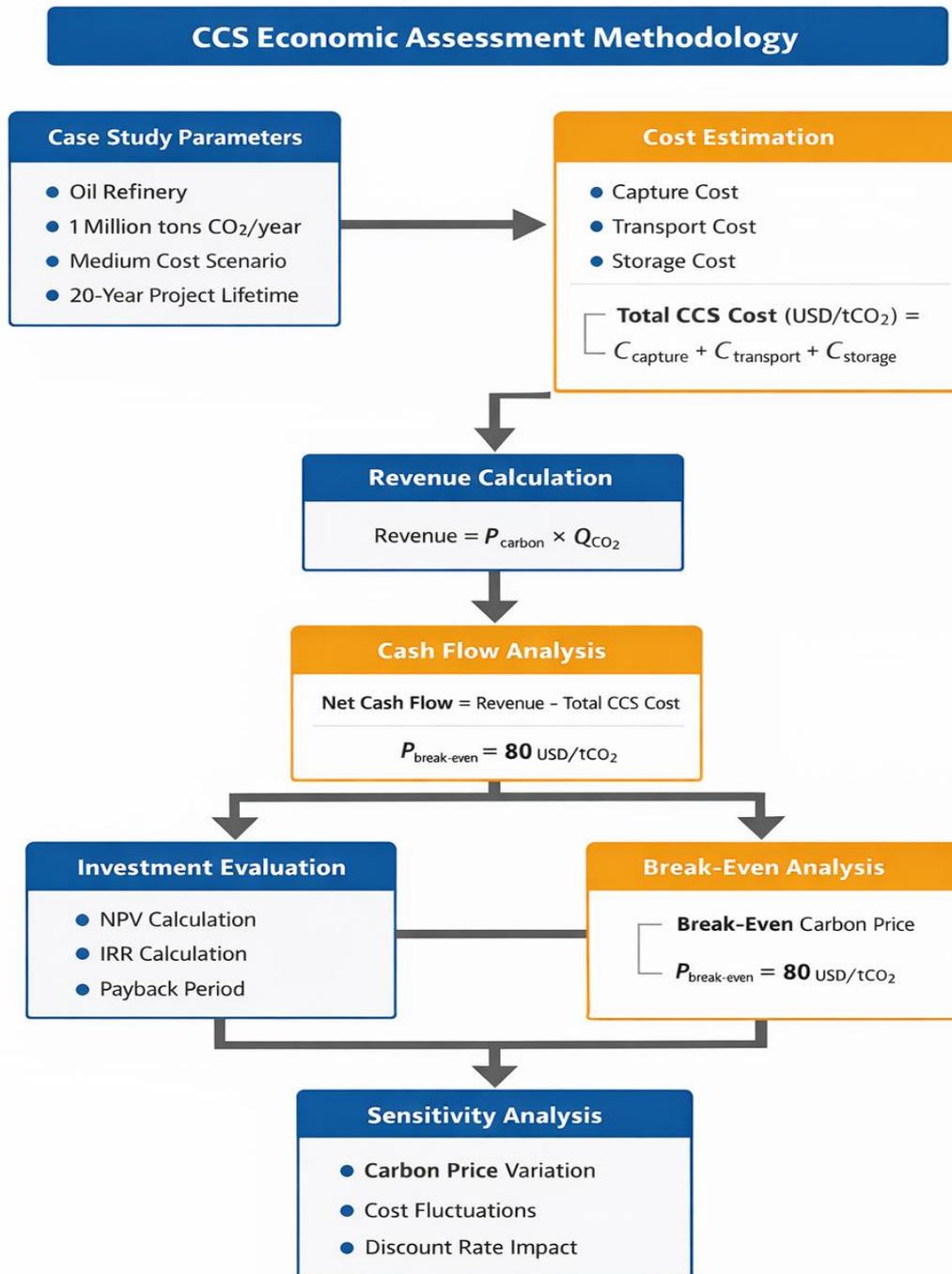


Fig 6:- Flowchart of the economic assessment methodology for Carbon Capture and Storage (CCS) implementation in an oil refinery capturing 1 million tons of CO₂ per year, illustrating the sequential steps of case study definition, cost estimation (capture, transport, and storage), revenue modelling, cash flow analysis, investment evaluation (NPV, IRR, and payback period), break-even carbon price determination, and sensitivity analysis.

Table6: 20-Year Discounted Cash Flow Analysis (Oil Refinery CCS Project)

Project Assumptions

Parameter	Value	Unit	Source / Basis
Industry Type	Oil Refinery	—	Industrial CCS application studies
Annual CO ₂ Captured	1,000,000	tons/year	Assumed mid-scale industrial CCS case
Capture Cost	\$50	USD/ton	International Energy Agency (CCUS Reports)
Transport Cost	\$12	USD/ton	Global CCS Institute Global Status Reports
Storage Cost	\$18	USD/ton	International Energy Agency
Total CCS Cost	\$80	USD/ton	Aggregated from the above sources
Carbon Price (Assumed)	\$100	USD/ton	Market scenario assumption
Project Lifetime	20	years	Typical CCS project evaluation horizon
Discount Rate	10%	%	Standard capital budgeting practice
Initial Investment (CAPEX)	\$600	Million USD	Industrial CCS capital cost benchmarks (IEA, GCCSI reports)

Table 7 :-20-Year Discounted Cash Flow Table

Year	Net Cash Flow (USD M)	Discount Factor (10%)	Present Value (USD M)
0	-600.00	1.000	-600.00
1	20.00	0.909	18.18
2	20.00	0.826	16.52
3	20.00	0.751	15.02
4	20.00	0.683	13.66
5	20.00	0.621	12.42
6	20.00	0.564	11.28
7	20.00	0.513	10.26
8	20.00	0.467	9.34
9	20.00	0.424	8.48
10	20.00	0.386	7.72
11	20.00	0.350	7.00
12	20.00	0.319	6.38
13	20.00	0.290	5.80
14	20.00	0.263	5.26
15	20.00	0.239	4.78
16	20.00	0.218	4.36
17	20.00	0.198	3.96
18	20.00	0.180	3.60
19	20.00	0.164	3.28
20	20.00	0.149	2.98

NPV (Net profit value calculation) :-

Step 1: Given Data

- Annual Net Cash Flow (NCF) = **\$20 million**
- Project Life (n) = **20 years**
- Discount Rate (r) = **10%**
- Initial Investment = **\$600 million**

✔ Step 2: NPV Formula

$$NPV = \sum_{t=1}^{20} \frac{NCF}{(1+r)^t} - \text{Initial Investment}$$

Since the annual cash flow is constant, we can use the **Present Value of Annuity Formula**:

$$PV = NCF \times \left(\frac{1 - (1+r)^{-n}}{r} \right)$$

✔ Step 3: Substitute Values

$$PV = 20 \times \left(\frac{1 - (1 + 0.10)^{-20}}{0.10} \right)$$

✔ Step 4: Solve Step-by-Step**1 Calculate $(1+0.10)^{20}$**

$$(1.10)^{20} = 6.7275$$

2 Take reciprocal:

$$(1.10)^{-20} = \frac{1}{6.7275} = 0.1486$$

3 Subtract from 1:

$$1 - 0.1486 = 0.8514$$

4 Divide by discount rate:

$$\frac{0.8514}{0.10} = 8.514$$

5 Multiply by Annual Cash Flow:

$$PV = 20 \times 8.514$$

$$PV = 170.28 \text{ million USD}$$

✔ Step 5: Calculate NPV

$$NPV = PV - \text{Initial Investment}$$

$$NPV = 170.28 - 600$$

$$NPV = -429.72 \text{ million USD}$$

✦ Final Result

$$NPV = -429.72 \text{ Million USD}$$

IRR CALCULATION :-The Internal Rate of Return (IRR) is calculated by determining the discount rate (r) at which the Net Present Value (NPV) becomes zero. For the refinery CCS project, the initial investment is USD 600 million and the annual net cash flow is USD 20 million over a 20-year project life. The IRR is obtained by solving the equation:

$$0 = \sum [20 / (1 + r)^t] - 600, \text{ where } t = 1 \text{ to } 20.$$

Since the annual cash flow is constant, the equation can be simplified using the annuity formula as:

$$600 = 20 \times [(1 - (1 + r)^{-20}) / r].$$

Dividing both sides by 20 gives:

$$30 = (1 - (1 + r)^{-20}) / r.$$

However, even at a zero-discount rate ($r = 0$), the total undiscounted cash inflow equals $20 \times 20 = 400$ million USD, which is less than the initial investment of 600 million USD. Therefore, the project cannot recover its capital cost under the assumed carbon price, and the IRR is negative. This indicates that the project is financially unviable without higher carbon prices, cost reductions, or policy support mechanisms.

The project fails to generate sufficient return to recover capital investment even at zero discount rate. Therefore:

- IRR is negative.
- The project is financially unattractive at \$100/ton carbon price.
- Higher carbon price or policy subsidy is required.

Sensitivity analysis table for CCS project: - The annuity factor is calculated using the Present Value Annuity Factor (PVAF) formula: $PVAF = [1 - (1 + r)^{-n}] / r$, where r is the discount rate and n is the number of years. For the CCS refinery project, the discount rate is 10% ($r = 0.10$) and the project life is 20 years ($n = 20$). Substituting these values into the formula gives: $PVAF = [1 - (1 + 0.10)^{-20}] / 0.10$. First, $(1.10)^{20} = 6.7275$. Taking the reciprocal gives $(1.10)^{-20} = 1 / 6.7275 = 0.1486$. Subtracting this from 1 result in $1 - 0.1486 = 0.8514$. Dividing by the discount rate yields $PVAF = 0.8514 / 0.10 = 8.514$. Therefore, the annuity factor is 8.514, meaning that one dollar received annually for 20 years at a 10% discount rate has a present value of 8.514 dollars.

Sensitivity Parameter: Carbon Price

$$\text{Annual Net Cash Flow} = (\text{Carbon Price} - 80) \times 1,000,000$$

$$\text{Present Value (PV)} = \text{Annual Cash Flow} \times 8.514$$

$$\text{NPV} = \text{PV} - 600$$

Sensitivity Table 8: Carbon Price vs NPV

Carbon Price (\$/ton)	Annual Net Cash Flow (\$M)	Present Value (\$M)	NPV (\$M)
80	0	0	-600
90	10	85.14	-514.86
100	20	170.28	-429.72
120	40	340.56	-259.44
150	70	595.98	-4.02
155	75	638.55	38.55
170	90	766.26	166.26

Key Insight

Break-even carbon price \approx **\$151–152 per ton**

At this level:

$$\text{NPV} \approx 0$$

The sensitivity analysis demonstrates that project viability is highly dependent on carbon pricing. At current moderate carbon prices (\sim \$100/ton), the refinery CCS project remains economically unviable. Financial feasibility is achieved only when the carbon price exceeds approximately \$150/ton, highlighting the importance of policy incentives, carbon markets, or subsidies.

IRR Sensitivity Table for my refinery CCS project.

Since the base case (carbon price = \$100/ton) gives **negative IRR**, we will test different carbon price levels to see how IRR changes.

Base Assumptions

- Industry: Oil Refinery
- CO₂ captured: 1 million tons/year
- Operating cost: \$80/ton
- Project life: 20 years
- Initial investment: \$600 million

$$\text{Annual Net Cash Flow} = (\text{Carbon Price} - 80) \times 1,000,000$$

IRR Sensitivity Table (Carbon Price vs IRR)(Table 9)

Carbon Price (\$/ton)	Annual Net Cash Flow (\$M)	Total 20-Year Cash Inflow (\$M)	IRR (%)
80	0	0	Not defined
90	10	200	Negative
100	20	400	Negative
120	40	800	≈ 2.6%
140	60	1,200	≈ 6.8%
150	70	1,400	≈ 9.8%
152	72	1,440	≈ 10.1%
170	90	1,800	≈ 14.4%

Key Findings

- IRR becomes positive when carbon price exceeds ~\$110/ton.
- IRR ≈ 10% when carbon price ≈ \$151–152/ton.
- Strong policy support is required for commercial viability.

The IRR sensitivity analysis demonstrates that the refinery CCS project is highly dependent on carbon pricing. At carbon prices below \$100 per ton, the project fails to generate a positive return. Financial feasibility improves significantly above \$140 per ton, and an IRR equal to the assumed 10% cost of capital is achieved at approximately \$152 per ton. This indicates that long-term carbon pricing mechanisms or government incentives are critical to ensuring investment attractiveness.

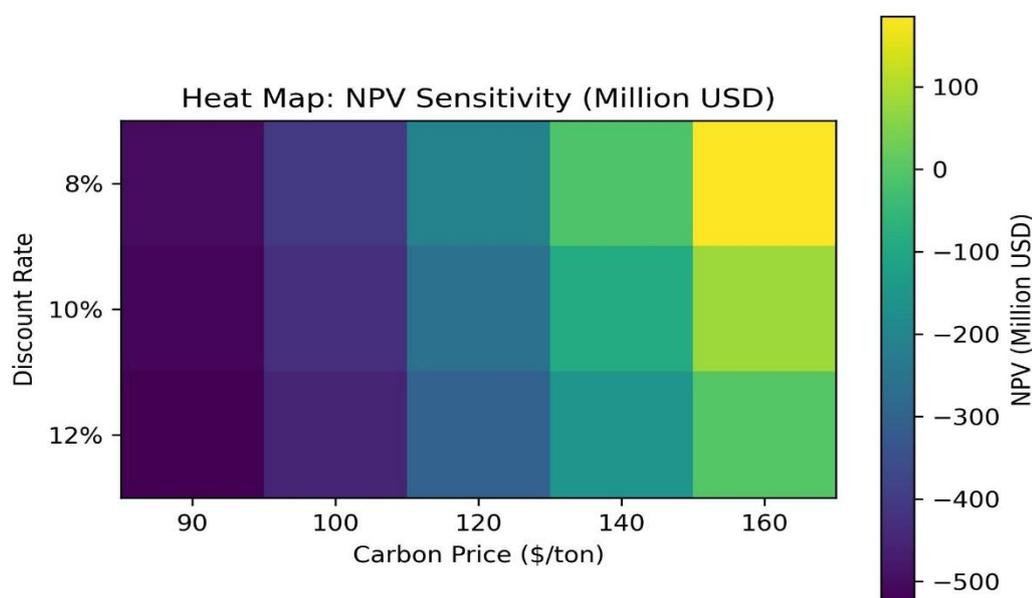


Fig 7 :-Heat map illustrating the combined sensitivity of Net Present Value (NPV) to variations in carbon price and discount rate for the refinery Carbon Capture and Storage (CCS) project. The horizontal axis represents carbon price scenarios (USD per ton), while the vertical axis represents discount rate variations (8–12%). The colour gradient indicates the magnitude of NPV (in million USD), highlighting the transition from negative to positive project viability. Results show that higher carbon prices and lower discount rates significantly improve economic feasibility, with break-even conditions occurring at carbon prices above approximately 150 USD per ton under moderate discount rates.

. Results and Discussion

1.1 Base Case Financial Performance

The financial evaluation of the refinery Carbon Capture and Storage (CCS) project was conducted under the base case assumptions of 1 million tons of CO₂ captured annually, a carbon price of 100 USD per ton, an operating cost of 80 USD per ton, a project life of 20 years, and a discount rate of 10%. The initial capital investment was assumed to be 600 million USD. Under these conditions, the annual net cash flow equals 20 million USD. Using an annuity factor of 8.514 (10% discount rate, 20 years), the total present value of inflows amounts to 170.28 million USD. Consequently, the Net Present Value (NPV) is -429.72 million USD, indicating significant financial infeasibility under current assumptions. The Internal Rate of Return (IRR) is negative, as the total undiscounted lifetime cash inflow (400 million USD) is lower than the initial investment. These findings demonstrate that, at a carbon price of 100 USD per ton, the project fails to recover capital costs.

1.2 Carbon Price Sensitivity The analysis reveals that carbon price is the most influential variable affecting financial viability. The NPV remains negative for carbon prices below approximately 150 USD per ton. Break-even occurs near 151–152 USD per ton, where NPV approaches zero, and IRR approximates the assumed 10% cost of capital. Beyond this threshold, project attractiveness improves rapidly, with substantial increases in both NPV and IRR. This result underscores the pivotal role of carbon pricing mechanisms in determining the feasibility of CCS investment.

1.3 Discount Rate Sensitivity: -The project's long-term cash flow structure makes it highly sensitive to the discount rate. Lower discount rates significantly improve present value outcomes, while higher rates reduce economic attractiveness. At 8%, the annuity factor increases, improving NPV compared to the 10% base case. Conversely, at 12%, NPV deteriorates further. This emphasises that financing structure, cost of capital, and perceived investment risk strongly influence CCS economics.

The project's long-term cash flow structure makes it highly sensitive to the discount rate. Lower discount rates significantly improve present value outcomes, while higher rates reduce economic attractiveness. At 8%, the annuity factor increases, improving NPV compared to the 10% base case. Conversely, at 12%, NPV deteriorates further. This emphasizes that financing structure, cost of capital, and perceived investment risk strongly influence CCS economics.

1.4 Combined Sensitivity Analysis

The combined sensitivity matrix (carbon price versus discount rate) demonstrates that economic feasibility requires both sufficiently high carbon pricing and moderate financing costs. Regions of positive NPV occur only at higher carbon price levels and lower discount rates. The analysis confirms that carbon price is the dominant driver, followed by capital cost and discount rate, while operational capture volume variations have comparatively smaller effects.

1.5 Policy and Strategic Implications

The results indicate that refinery-based CCS projects are unlikely to be financially viable under moderate carbon pricing without policy intervention. Financial attractiveness can be enhanced through:

- Higher carbon pricing mechanisms
- Investment tax credits or capital subsidies
- Lower financing costs via green bonds or concessional loans
- Technological innovation reduces capture costs

The economic gap identified in this study suggests that large-scale CCS deployment in refining sectors depends heavily on regulatory stability and long-term carbon market certainty.

1.6 Overall Assessment

The financial analysis demonstrates that CCS projects in carbon-intensive industries such as oil refineries face substantial economic barriers under current market conditions. While technically feasible, their commercial viability is strongly contingent upon policy frameworks and carbon pricing structures. Therefore, the economic sustainability of CCS requires integrated financial planning, risk mitigation strategies, and supportive regulatory environments.

Conclusion :-This study evaluated the economic viability of a Carbon Capture and Storage (CCS) project implemented in an oil refinery capturing 1 million tons of CO₂ annually over a 20-year project life. Using a medium-cost scenario, an initial capital investment of 600 million USD, and a 10% discount rate, the financial analysis revealed a negative Net Present Value (-429.72 million USD) at a carbon price of 100 USD per ton. The Internal Rate of Return (IRR) was found to be negative, indicating that the project fails to recover its capital investment under current market conditions.

Sensitivity analysis demonstrated that the carbon price is the most critical determinant of project feasibility. Break-even occurs at approximately 150–152 USD per ton, where NPV approaches zero, and IRR aligns with the 10% cost of capital. The results confirm that refinery-based CCS projects are highly sensitive to policy-driven variables, particularly carbon pricing and financing conditions. While technically feasible, the project remains economically unattractive without stronger regulatory and financial support mechanisms.

Overall, the study concludes that large-scale CCS deployment in refinery operations requires robust carbon markets, reduced capital costs, and supportive financial frameworks to achieve commercial sustainability.

Limitations of the Study

Although the analysis provides valuable insights into CCS's financial performance, several limitations must be acknowledged:

- 1. Static Cost Assumptions:** The study assumes constant operating costs and carbon prices over the 20-year project life. In reality, these variables are subject to market volatility and technological change.
- 2. Single-Industry Case Study:** The analysis focuses exclusively on an oil refinery scenario. Results may differ significantly for power plants, cement industries, or steel sectors due to varying emission intensities and cost structures.
- 3. Exclusion of Policy Incentives:** The model does not explicitly incorporate tax credits, grants, carbon offsets, or revenue from enhanced oil recovery (EOR), which may substantially improve project economics.
- 4. Simplified Financing Structure:** The discount rate is assumed constant at 10%, without differentiating between debt-equity structures or risk-adjusted financing models.
- 5. No Real Options Analysis:** The study does not account for managerial flexibility, phased investments, or future expansion decisions that could affect project valuation.

Future research should integrate stochastic modelling, dynamic carbon pricing scenarios, and hybrid revenue streams to provide a more comprehensive economic evaluation.

Policy Recommendations

Based on the findings, the following policy recommendations are proposed to enhance CCS financial feasibility:

1.1 Strengthen Carbon Pricing Mechanisms

Carbon prices must exceed approximately 150 USD per ton to achieve financial viability under the assumed cost structure. Governments should implement stable and predictable carbon pricing systems, such as emissions trading schemes or carbon taxes, to provide long-term investment certainty.

1.2 Provide Capital Subsidies and Tax Credits

Upfront capital expenditure represents the largest economic barrier. Investment tax credits, accelerated depreciation, and direct capital grants can significantly reduce financial risk and improve NPV outcomes.

1.3 Reduce Financing Costs

Governments and financial institutions should promote green bonds, concessional loans, and blended finance mechanisms to lower the cost of capital. Reduced discount rates substantially improve long-term CCS economics.

1.4 Encourage Technological Innovation

Research and development support should focus on reducing capture costs through advanced solvents, membrane technologies, and process optimisation. Lower operating costs directly improve project returns.

1.5 Develop Integrated Carbon Infrastructure

Shared transport and storage networks can reduce individual project costs and create economies of scale, improving economic viability across multiple industries.

Future Research Directions

Future research should focus on developing more dynamic and integrated economic models for Carbon Capture and Storage (CCS) projects by incorporating stochastic carbon price scenarios, inflation-adjusted operating costs, and real options analysis to account for managerial flexibility and phased investments. Expanding the assessment to multi-industry comparisons—such as power generation, cement, and steel sectors—would provide broader insights into sector-specific viability thresholds. Additionally, future studies should integrate hybrid revenue mechanisms, including carbon credits, enhanced oil recovery (EOR), hydrogen co-production, and negative emissions markets. Incorporating life-cycle assessment (LCA) and environmental cost-benefit analysis would further strengthen the sustainability evaluation. Advanced risk modelling using Monte Carlo simulation and probabilistic sensitivity analysis can also improve investment decision frameworks under uncertainty. Finally, policy-focused research examining carbon market stability, international financing mechanisms, and cross-border carbon infrastructure development will be essential to guide large-scale CCS deployment strategies.

Bibliography

International Energy Agency (IEA). (2023). *CCUS in clean energy transitions*. Paris: International Energy Agency.

International Energy Agency (IEA). (2022). *Global status of CCS 2022*. Paris: International Energy Agency.

Global CCS Institute. (2023). *Global status of CCS report 2023*. Melbourne: Global CCS Institute.

Rubin, E. S., Davison, J. E., & Herzog, H. J. (2015). The cost of CO₂ capture and storage. *International Journal of Greenhouse Gas Control*, 40, 378–400.

Rubin, E. S., Short, C., Booras, G., Davison, J., Ekstrom, C., Matuszewski, M., & McCoy, S. (2013). A proposed methodology for CO₂ captures and storage cost estimates. *International Journal of Greenhouse Gas Control*, 17, 488–503.

ZEP (Zero Emissions Platform). (2011). *The costs of CO₂ capture, transport and storage*. European Technology Platform for Zero Emission Fossil Fuel Power Plants.

IEAGHG (International Energy Agency Greenhouse Gas R&D Programme). (2019). *Techno-economic evaluation of CCS projects*. Cheltenham: IEAGHG.

Haszeldine, R. S. (2009). Carbon capture and storage: How green can black be? *Science*, 325(5948), 1647–1652.

GCCSI (Global CCS Institute). (2022). *The economic potential of carbon capture*. Melbourne: Global CCS Institute.

United Nations Environment Programme (UNEP). (2023). *Emissions gap report 2023*. Nairobi: UNEP.

Acknowledgement

The author sincerely acknowledges the valuable academic guidance, technical insights, and financial management concepts that contributed to the successful completion of this study on the economic viability of Carbon Capture and Storage (CCS). Special appreciation is extended to colleagues and mentors for their constructive discussions on carbon pricing mechanisms, project finance modelling, and sustainability assessment. The author also recognizes the contributions of international organizations such as the International Energy Agency (IEA) and the Global CCS Institute for providing comprehensive data and reports that supported the financial analysis. Finally, heartfelt gratitude is expressed to family members for their continuous encouragement and moral support throughout the research process.