Eco-Business & Environmental Progress Journal
Journal Homepage: www.ecobusinessjournal.org

Vol. 5, No. 1
Article ID: EBEPJ-2025002

Evaluating the Economic Feasibility of Industrial Carbon Capture and Storage (CCS) in Emerging Economies

Mrittika Sen Gupta[1]*, Md Rasel Ul Alam[2], Md. Farhan Islam Alvi[3]
[1] *North South University, Dhaka, Bangladesh*
[2] *University of the Cumberland, Kentucky, USA*
[3] *Jagannath University, Dhaka, Bangladesh *Corresponding author: mrittika.nsu12@gmail.com*

Received 14 January 2025; Revised 12 April 2025; Accepted 22 May 2025; Published: 19 July 2025

KEYWORDS

Carbon Capture and Storage, Techno-Economic Analysis, Net Present Value, Industrial Decarbonization, Policy Engineering, Blended Finance

Abstract

Industrial decarbonization in emerging economies presents a profound strategic challenge due to high upfront capital requirements, volatile energy markets, and elevated sovereign risk premiums. This study provides an expanded techno-economic evaluation of the financial viability of integrating point-source Carbon Capture and Storage (CCS) technology within heavy industrial clusters in developing nations. Utilizing an extended quantitative cash flow model based on Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Carbon Abated (LCCA), we analyze a representative 1.5 Mt CO2/year industrial facility over a 20-year operational life cycle. Empirical modeling indicates that under an unassisted baseline market with a nominal $35/t CO2 credit, standalone CCS retrofitting incurs a net present loss of -$142.5 million. However, evaluating the asset under a multi-tiered policy framework combining a $65/t CO2 credit, a 20% capital grant, and blended green bond financing that lowers the WACC from 10% to 6.5% transforms project economics, yielding a positive NPV of $89.6 million and an IRR of 14.1%. Extensive sensitivity analysis demonstrates that project viability is most vulnerable to thermal energy regeneration costs and carbon credit volatility. Regional WACC benchmarking across Latin America, Southeast Asia, Sub-Saharan Africa, South Asia, and the Middle East underscores the necessity of concessional derisking facilities. Policy recommendations advocate for regional shared CCUS hub infrastructure to distribute capital risks, achieve scale economies, and accelerate private sector participation.

1. Introduction

Achieving the Paris Agreement target of limiting global warming to 1.5°C requires rapid and systemic reductions in greenhouse gas emissions across all sectors of the global economy (Herzog, 2011; Subraveti et al., 2023; IPCC, 2023). Although decarbonization in the power sector has accelerated through the deployment of solar photovoltaic systems and onshore and offshore wind technologies, hard-to-abate industrial sectors—including cement, integrated steelmaking, chemicals, and petroleum refining—remain highly dependent on fossil fuels for high-temperature process heat and chemical feedstocks (Wang et al., 2024; Global CCS Institute, 2023). In these industries, a substantial share of CO_2 emissions is generated directly by industrial processes rather than electricity consumption. For example, cement production releases process-related CO_2 through the calcination of limestone, where calcium carbonate ($CaCO_3$) is converted into calcium oxide (CaO) and CO_2. Such emissions cannot be completely eliminated through renewable electricity substitution alone (Bergstrom & Ty, 2017; IEA, 2023). Figure 1 illustrates the complete industrial point-source CCS value chain, from flue-gas capture and conditioning through transportation, utilization, and geological storage. Emerging and developing economies account for an increasingly important share of global industrial production, primary-material processing, and infrastructure development (World Bank, 2023). Countries across Southeast Asia, Latin America, Sub-Saharan Africa, South Asia, and the Middle East therefore face a complex dual challenge: sustaining industrialization, employment, urban development, and poverty reduction while simultaneously meeting increasingly stringent climate commitments under the Paris Agreement and updated Nationally Determined Contributions (NDCs) (Naseeb et al., 2022; ADB, 2023). Premature retirement of productive industrial assets could impose substantial economic and social costs, particularly in economies where manufacturing remains an important source of employment, exports, and fiscal revenue (Mattoo et al., 2012; UNCTAD, 2021). Consequently, Carbon Capture and Storage (CCS) represents an important technological pathway for reducing emissions from existing industrial facilities while allowing essential industrial production to continue during the transition toward lower-carbon economies (Lyon & Montgomery, 2015; Böhringer et al., 2018; Bui et al., 2018). Despite considerable technological development in post-combustion capture, commercial deployment of industrial CCS in emerging markets remains limited (Roussanaly et al., 2021). The principal constraints are increasingly economic, financial, and institutional rather than purely technical. Industrial CCS retrofits require substantial upfront capital expenditure (CAPEX), generate additional operating expenditure (OPEX), and may impose significant energy penalties associated with solvent regeneration and compression. At the same time, projects located in emerging economies frequently face higher sovereign risk, currency uncertainty, limited domestic financing capacity, and elevated Weighted Average Cost of Capital (WACC), all of which substantially reduce the present value of future carbon-related revenues (Subraveti et al., 2023;

Zapantis et al., 2021). Consequently, technically feasible CCS projects may remain financially unattractive under conventional commercial financing conditions (Finkenrath, 2011).

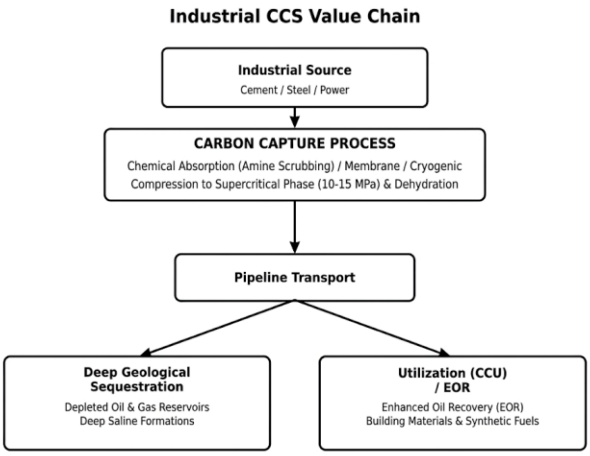

Figure 1. Schematic of the Industrial Point-Source CCS Value Chain.

The financial challenge is further intensified by uncertainty surrounding future carbon prices, energy costs, regulatory incentives, and long-term storage liabilities.

A project may therefore demonstrate strong technical performance while simultaneously producing a negative Net Present Value (NPV) when evaluated using market-based discount rates. This creates a fundamental distinction between technical feasibility and financial bankability.

A commercially viable CCS investment must not only capture and permanently store CO_2 at an acceptable cost but also generate sufficient risk-adjusted returns to compensate private investors for capital, policy, operational, and market uncertainties.

To address these constraints, this study develops an integrated techno-economic framework for evaluating industrial CCS in emerging economies. The analysis combines Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Carbon Abated (LCCA) to evaluate project performance under alternative financing and policy scenarios.

Particular attention is given to the interaction between carbon incentives, capital grants, concessional financing, and WACC reduction. The study also evaluates whether shared regional CCUS infrastructure can generate scale economies by distributing transportation, storage, monitoring, and network-development costs across multiple industrial facilities. Accordingly, the study addresses four principal research objectives:

(1) to estimate the baseline levelized cost of carbon abatement for industrial CCS under different flue-gas characteristics; **(2)** to quantify the financial effects of carbon credits, capital grants, and concessional financing on CCS project NPV and IRR; **(3)** to assess project sensitivity to energy-price, carbon-price, and discount-rate uncertainty; and **(4)** to examine the economic advantages of shared regional CCUS hubs relative to isolated facility-level CCS deployment.

2. Literature Review

2.1 Evolution of CCS Techno-Economics and Flue Gas Stream Dynamics

Early techno-economic research on carbon capture concentrated primarily on fossil-fuel power-generation facilities in developed economies (Herzog, 2011; Finkenrath, 2011; Rubin et al., 2015). These studies established that post-combustion capture, particularly solvent-based amine absorption, can impose substantial energy and cost penalties because significant quantities of thermal energy are required for solvent regeneration. Consequently, the economics of CCS are strongly influenced by the characteristics of the emission source, energy requirements, plant utilization rate, and transportation and storage configuration. More recent research has increasingly shifted toward industrial applications, where the economic and technical characteristics of CO_2 capture differ substantially across sectors (Leeson et al., 2017; Roussanaly et al., 2021). Industrial facilities produce emission streams with different CO_2 concentrations, pressures, temperatures, impurities, and operating profiles. High-purity CO_2 streams, such as those associated with hydrogen production or natural-gas processing, can require comparatively less energy-intensive separation.

In contrast, cement kilns and steel facilities generally require more complex capture configurations because CO_2 is generated through a combination of fuel combustion and process chemistry. The concentration and composition of the flue gas therefore have direct implications for capture cost and energy consumption. Higher CO_2 concentrations generally reduce the separation burden, whereas dilute streams require greater energy and equipment requirements. Similarly, industrial facilities with stable and continuous operating schedules may provide more favorable utilization rates for capture equipment than facilities characterized by highly variable production. These differences demonstrate why a single average CCS cost cannot adequately represent the economics of industrial decarbonization across sectors. The literature also emphasizes that capture represents only one component of the overall CCS value chain. Captured CO_2 must subsequently be compressed, transported, monitored, and permanently stored or utilized. Consequently, project economics depend on the combined cost of capture, conditioning, transportation, injection, monitoring, and long-term storage. This integrated perspective is particularly important for emerging economies, where dedicated CO_2 transportation networks and geological storage infrastructure may not yet exist.

2.2 Capital Constraints and Risk Governance in Emerging Economies

Although the underlying engineering principles of CCS are broadly transferable across countries, the financial environment in which projects are developed varies substantially. Emerging economies frequently face higher sovereign risk premiums, currency volatility, relatively shallow capital markets, and limited access to long-term infrastructure finance (Naseeb et al., 2022; World Bank, 2023). These conditions increase the WACC applied to large industrial decarbonization projects and can significantly reduce the present value of future carbon-related revenues. The importance of WACC is particularly pronounced for CCS because project expenditures are heavily front-loaded. Large amounts of capital must be committed before the project generates operational benefits or carbon-related revenues. As the discount rate increases, future cash flows are discounted more heavily, causing otherwise technically viable projects to produce lower or negative NPVs. Thus, differences in financing conditions can fundamentally change the investment decision even when the underlying capture technology remains identical. Enterprise Risk Management (ERM) provides an additional perspective for understanding these investment challenges. Industrial CCS projects are exposed to multiple categories of risk, including regulatory uncertainty, energy-price volatility, technology-performance risk, carbon-price uncertainty, and long-term storage liability (COSO, 2017; ISO, 2018; Alam et al., 2024). These risks interact rather than operating independently. For example, an increase in energy prices can simultaneously increase CCS operating costs and reduce project cash flow, while uncertainty regarding future carbon prices can make investors reluctant to commit capital to projects with long payback periods. From a policy perspective, the literature suggests that public intervention may be required to address risk components that private investors cannot efficiently absorb. Supply-side mechanisms include capital grants, concessional loans, accelerated depreciation, and public infrastructure investment, while demand-side mechanisms include carbon pricing, tax credits, contracts-for-difference, and guaranteed carbon-abatement payments (Böhringer et al., 2018; Helm, 2010; Wang et al., 2024). The effectiveness of these instruments depends not only on their individual magnitude but also on how they interact within the overall project-financing structure. This suggests that CCS policy should not be evaluated solely by asking whether a particular carbon price is sufficiently high. Instead, policy design should consider the combined effect of carbon incentives, capital support, financing costs, and infrastructure availability. This study therefore evaluates a multi-tiered policy package rather than examining individual policy instruments in isolation.

2.3 Commercial Utilization (CCUS) and Scale Economies

Carbon Capture, Utilization, and Storage (CCUS) can provide an alternative pathway for early-stage deployment in regions where permanent storage markets and carbon-pricing systems remain underdeveloped. Captured CO_2 may potentially be utilized for applications such as enhanced oil recovery, mineralization, synthetic fuels, chemicals, and construction materials, depending on local geological and industrial conditions (Hepburn et al., 2019; Tapia et al., 2018). The economic value of utilization depends on the quality of the captured CO_2, transportation distance, processing requirements, market demand, and long-term contractual arrangements. Although utilization can generate additional revenue, it does not necessarily provide a universal substitute for permanent geological storage. Some utilization pathways have limited capacity, while others may require additional energy inputs or generate only temporary carbon retention. Therefore, the financial model should distinguish between revenue-generating utilization pathways and permanent storage options rather than treating all CCUS applications as economically equivalent. An additional area of importance is the development of shared CCUS hubs. Individual industrial facilities may face prohibitive transportation and storage costs when attempting to develop dedicated infrastructure. A regional hub can allow multiple emitters to share CO_2 pipelines, compression facilities, monitoring systems, injection infrastructure, and storage reservoirs. Such infrastructure sharing can reduce the average cost per tonne of CO_2 transported and stored while improving utilization rates of common infrastructure. The hub model is particularly relevant to emerging economies because individual industrial facilities may lack the financial capacity to independently develop complete CCS infrastructure. By aggregating emissions from multiple cement, steel, chemical, and refining facilities, a regional CCUS network can potentially create sufficient scale to attract private investment and public infrastructure support. This provides a strong economic rationale for evaluating CCS not only at the individual-facility level but also at the **industrial-cluster level**.

Table 1. Flue Gas Technical Characteristics and Abatement Cost Benchmarks Across Industrial Sectors.

Industrial Sector	CO2 Concentration	Energy Penalty	Capture Cost	Storage Type
Natural Gas Processing	80% - 95%	1.2 GJ/t CO2	$18 - $28/t	EOR / Aquifer
Chemical Synthesis	60% - 85%	1.8 GJ/t CO2	$25 - $38/t	Deep Saline
Cement Kilns	18% - 28%	3.2 GJ/t CO2	$48 - $68/t	Aquifer / Storage
Blast Furnace Steel	15% - 25%	3.6 GJ/t CO2	$52 - $75/t	Depleted Gas
Gas-Fired Power	4% - 9%	4.5 GJ/t CO2	$85 - $120/t	Geological Basin

2.4 Literature Gap and Research Positioning

Techno-economic assessment of CCS generally relies on several complementary financial indicators. Among these, Net Present Value (NPV) provides a direct measure of whether the discounted future benefits of the project exceed the initial investment. A positive NPV indicates that the project generates value above the assumed discount rate, whereas a negative NPV indicates that the expected cash flows are insufficient to compensate investors for the required capital and risk. The Internal Rate of Return (IRR) provides a complementary measure by identifying the discount rate at which the project's NPV becomes zero. Comparing IRR with the project's WACC provides an indication of financial attractiveness. A project with an IRR above its WACC may be considered financially viable under the modeled assumptions, whereas an IRR below WACC indicates insufficient risk-adjusted returns. The Levelized Cost of Carbon Abated (LCCA) provides a different perspective by measuring the average cost associated with each tonne of CO_2 avoided over the project's lifetime. LCCA is particularly useful for comparing alternative industrial decarbonization technologies and evaluating whether the cost of CCS is consistent with prevailing or expected carbon prices. Importantly, these three indicators answer different questions. NPV evaluates total investment value, IRR evaluates the project's implied rate of return, and LCCA evaluates the cost-effectiveness of emissions reduction. Using all three indicators therefore provides a more comprehensive assessment than relying on a single financial metric.

2.5 Policy Engineering and Blended Finance

The literature increasingly recognizes that industrial decarbonization in emerging markets may require financial structures that combine public and private capital. Traditional commercial financing can impose high WACC because investors price sovereign, currency, technology, and policy risks into the cost of capital. Blended finance can partially address these constraints by combining concessional capital with commercial debt and equity. A reduction in WACC can have a particularly strong effect on CCS projects because of their capital-intensive structure and long operating life. Lower-cost financing increases the present value of future carbon revenues and reduces the financial burden associated with initial CAPEX. Similarly, capital grants can reduce the amount of private capital required at project initiation, while carbon credits or guaranteed carbon payments can improve recurring operating revenues. The interaction among these mechanisms is important. A moderate carbon incentive may be insufficient when WACC is high, while a substantial capital grant may still fail to produce adequate returns if long-term operating revenues remain uncertain. A coordinated policy package can therefore be more effective than isolated interventions. This study contributes to this literature by explicitly modeling the combined effects of carbon credits, capital grants, and concessional financing within a unified NPV and IRR framework.

2.6 Sensitivity and Risk Analysis

CCS project economics are inherently sensitive to uncertain market and technical parameters. Energy prices represent one of the most important variables because capture systems can require substantial quantities of thermal and electrical energy. An increase in energy prices can therefore increase OPEX and reduce the project's net cash flow. Carbon-price volatility represents another major source of uncertainty. Because many CCS projects depend partly on carbon credits or avoided-emission revenues, changes in the value of carbon can materially alter project profitability. Similarly, increases in WACC can sharply reduce NPV because future revenues are discounted at a higher rate. Sensitivity analysis is therefore essential for evaluating whether a project's apparent profitability is robust or depends on a narrow combination of favorable assumptions. Scenario analysis can further distinguish between baseline, moderate-policy-support, and strong-policy-support environments. Such analysis is especially important for emerging economies where macroeconomic conditions and regulatory frameworks can change rapidly. The present study extends this approach by stress-testing CCS economics across changes in energy regeneration costs, carbon-credit values, WACC, capital support, and infrastructure configuration. This allows the analysis to identify not only whether a project is financially viable but also which variables represent the greatest threats to long-term bankability.

2.7 Literature Gap and Research Positioning

Despite substantial research on CCS technology and techno-economic performance, several important gaps remain. First, a significant proportion of existing techno-economic research has focused on developed economies, where financing conditions, infrastructure availability, and regulatory institutions differ substantially from those of emerging markets. Consequently, conventional CCS cost estimates may not adequately capture the higher WACC and financing constraints faced by industrial facilities in developing economies. Second, existing policy studies frequently evaluate individual policy instruments independently. Less attention has been given to the combined financial effect of carbon incentives, capital grants, and concessional financing within a single project-level cash-flow model. This limits the ability of policymakers to determine which combination of instruments is sufficient to transform a technically feasible CCS project into a financially bankable investment. Third, relatively limited attention has been given to the interaction between CCS economics and shared regional infrastructure. Most facility-level assessments implicitly assume that individual industrial plants can access suitable transportation and storage infrastructure. In emerging economies, however, such infrastructure may need to be developed collectively across multiple emitters. The resulting economies of scale could materially change the cost structure and investment case.

Fourth, many assessments emphasize capture costs without sufficiently integrating financing risk, carbon-price uncertainty, and long-term infrastructure economics into a unified framework. This is particularly problematic for emerging economies, where financial and institutional risks can be as important as technological performance. Finally, there remains a need for policy-oriented techno-economic models that translate financial results into practical deployment strategies. A positive NPV under ideal financing conditions is insufficient evidence for large-scale deployment if the required financing structure is unavailable in the target market. This study addresses these gaps through an integrated quantitative framework combining NPV, IRR, LCCA, sensitivity analysis, blended-finance scenarios, and regional CCUS hub evaluation. The analysis evaluates a representative 1.5 Mt CO_2/year industrial facility over a 20-year operating period and compares baseline market conditions with progressively stronger policy-support scenarios. By linking project-level economics with financing conditions and infrastructure scale, the study provides a more comprehensive assessment of the conditions required for industrial CCS deployment in emerging economies. The framework ultimately positions financial de-risking and infrastructure coordination as complementary components of industrial CCS policy. Rather than assuming that technological maturity alone will produce widespread deployment, the analysis evaluates how policy support can alter the investment equation and reduce the gap between technical feasibility and commercial bankability. This perspective provides a basis for designing regionally appropriate CCS strategies that can mobilize private capital while maintaining the broader objective of cost-effective industrial decarbonization.

3. Methodology

3.1 Mathematical Model Formulation

Project financial performance is evaluated using an extended quantitative discounted cash flow (DCF) model for a representative 1.5 Mt CO_2/year industrial carbon capture and storage/utilization facility over a 20-year operational lifespan (($N=20$)), preceded by a three-year construction phase (($t=-3,-2,-1$)). The model evaluates the economic feasibility of the facility by incorporating initial capital investment, annual operating expenditures, carbon-related revenues, utilization revenues, taxation, financing costs, and the time value of money. This structure enables the comparison of alternative policy and market scenarios under different carbon prices, utilization revenues, and financing conditions. The construction-period investment is distributed across the three pre-operational years rather than being treated as a single instantaneous expenditure. This approach allows the model to represent the timing of capital deployment and its corresponding impact on present value. Construction expenditures occurring earlier in the project timeline receive greater discounting effects when converted to the project valuation date. Once the facility becomes operational, annual cash flows are generated from captured CO_2 and associated utilization or storage services.

Equation (1) Net Present Value:

$$NPV = \sum_{t=1}^{N} \frac{CF_t}{(1+r)^t} - \sum_{k=1}^{3} \frac{CAPEX_k}{(1+r)^K} \quad (1)$$

Where represents the net operating cash flow in operational year t, represents the capital expenditure incurred during construction year k, and represents the project's weighted average cost of capital. A positive NPV indicates that the discounted project cash inflows exceed the required investment and associated costs under the specified assumptions.

Equation (2). Annual Operational Cash Flow

$$CF_t = Q_t(P_{carbon} + P_{utilization}) - [OPEX_{fixed} + Q(OPEX_{energy} + OPEX_{other} + C_{transport}) + Tax_t]$$

The annual cash-flow formulation captures the interaction between project revenues and operating costs. Carbon-related revenue is determined by the volume of CO_2 captured and the applicable carbon offset or policy value. Additional revenue may be generated when captured CO_2 is utilized for enhanced oil recovery (EOR) or other commercial applications. The model therefore allows the utilization revenue component to vary independently from the carbon policy value, reflecting uncertainty in downstream CO_2 markets. The model also distinguishes between fixed and variable operating expenditures. Fixed operating costs remain relatively stable with changes in annual throughput, whereas energy consumption, transportation, and other process-related expenses vary according to the quantity of CO_2 captured and processed. This distinction is important because facilities operating below their nominal capture capacity may experience higher unit costs as fixed expenditures are distributed over a smaller volume of captured CO_2.

Equation (3) Levelized Cost of Abated Carbon:

$$LCCA = \frac{CAPEX_0 \left[\frac{r(1+r)^N}{(1+r)^N - 1}\right] + OPEX_{annual}}{Q_{captured,annual}} \quad (2)$$

The Levelized Cost of Abated Carbon (LCCA) provides a normalized measure of the cost associated with capturing and managing one tonne of CO_2 over the project's operational lifetime. The capital recovery factor converts the initial investment into an equivalent annualized cost based on the selected discount rate and operating period. LCCA therefore facilitates comparison between the modeled facility and alternative carbon-abatement technologies or policy benchmarks. Where (Q) represents annual captured volume (1.5 Mt CO_2/year), ($CAPEX_0$) is baseline capital expenditure ($225 million), (r) is the Weighted Average Cost of Capital (WACC), ($P_{\{carbon\}}$) is the policy carbon offset value ($35–$65/t CO_2), ($P_{\{utilization\}}$) EOR off-take revenue ($0–$30/t CO_2), ($OPEX_{\{energy\}}$) is variable thermal/electric power cost ($28/t CO_2), and ($C_{\{transport\}}$) is pipeline and storage overhead ($12/t CO_2). To account for uncertainty in the external policy and market environment, the model evaluates multiple carbon-price and utilization-revenue scenarios. The carbon offset value is treated as a principal policy variable because changes in carbon-credit valuation can substantially affect project revenue and investment attractiveness. Similarly, the EOR utilization value is modeled over a range from zero to $30/t CO_2 to represent scenarios ranging from pure storage without utilization revenue to commercially favorable CO_2 utilization conditions.

Capital expenditure is further adjusted for differences in facility scale using a non-linear capital scaling relationship:

$$CAPEX_{scale} = CAPEX_0 \times \left(\frac{Q_{new}}{Q_0}\right)^{0.60} \quad (3)$$

where ($Q_{\{new\}}$)epresents the capacity of the alternative facility and (Q_0) represents the reference capacity of 1.5 Mt CO_2/year. The exponent of 0.60 captures economies of scale, implying that capital requirements increase less than proportionally as capture capacity increases. Consequently, larger facilities may achieve lower capital expenditure per tonne of annual capture capacity, although their absolute investment requirement remains higher. The model also incorporates capacity utilization as an important operational parameter. The nominal capture capacity of 1.5 Mt CO_2/year represents full utilization, while scenario analysis can evaluate lower operating rates to account for equipment downtime, maintenance, feedstock variability, and ramp-up effects during the early operational years. Actual annual captured volume can therefore be represented as the product of nominal capacity and the applicable utilization factor. Finally, the framework is designed to support sensitivity and scenario analysis. Key uncertain parameters including WACC, carbon offset value, EOR revenue, CAPEX, energy cost, transportation cost, and facility utilization can be varied individually or simultaneously to identify their effects on NPV and LCCA. This allows the financial framework to distinguish between projects that remain economically viable across a broad range of market conditions and projects whose profitability depends heavily on favorable policy incentives or utilization revenues. The resulting financial indicators provide a quantitative basis for evaluating investment risk and determining the policy conditions required for long-term deployment of large-scale carbon capture infrastructure.

3.2 Financial Assumptions, Risk Treatment, and Scenario Analysis

In addition to the core DCF formulation, the financial framework incorporates a set of operational and financing assumptions to capture the major sources of uncertainty associated with large-scale carbon capture projects. The model distinguishes between capital costs incurred during the construction period and recurring operating expenditures during the 20-year operational period. This distinction is necessary because capital-intensive carbon capture facilities typically require substantial upfront investment before generating any project revenue. Construction expenditure is assumed to occur during the three-year development period, with the timing of individual capital outlays explicitly represented in the DCF model. Engineering, procurement, construction, equipment installation, commissioning, and associated infrastructure costs are included within the total CAPEX envelope. The model can distribute the baseline $225 million investment across the three construction years according to a predefined expenditure schedule. This approach prevents the analysis from treating the entire capital requirement as an instantaneous investment and provides a more realistic representation of project financing requirements. The operational period begins following completion of the construction phase. During the initial operating years, the facility may operate below its nominal 1.5 Mt CO_2/year capacity because of commissioning requirements, equipment optimization, maintenance, and gradual operational ramp-up. The model permits the annual capture volume to vary according to a capacity-utilization factor: $Q_t = Q_{nominal} \times U_t$ where (Q_t) is the actual quantity of CO_2 captured in year (t), (Q_{nominal}) is the nominal annual capture capacity, and (U_t) is the utilization factor ranging from 0 to 1. This formulation allows the model to evaluate both full-capacity operation and lower-utilization scenarios. The revenue structure is divided into two principal components: carbon-policy revenue and CO_2 utilization revenue. Carbon-policy revenue represents financial compensation associated with verified CO_2 capture, storage, or carbon-abatement credits. Utilization revenue represents additional income obtained when captured CO_2 is supplied to an EOR operation or another commercial utilization pathway. The model treats these revenue streams independently because a facility may receive policy-based compensation even when no utilization market is available. The financial model also accounts for the possibility that carbon-policy values may change over the project's lifetime. Rather than assuming a single permanent carbon price, alternative scenarios can be evaluated using low, central, and high carbon-value trajectories. This allows the analysis to determine whether project economics remain viable under declining, constant, or increasing policy support. Such treatment is particularly important because carbon capture projects often depend on long-term regulatory incentives and carbon-market conditions. Operating expenditures are separated into fixed and variable components. Fixed OPEX includes expenses such as staffing, facility administration, maintenance contracts, insurance, monitoring, and general site operations. Variable OPEX is associated primarily with energy consumption, process chemicals, CO_2 conditioning, compression, transportation, and storage. The variable-cost formulation ensures that changes in annual throughput directly affect total operating expenditure.

Table 2. Baseline Financial and Operational Parameters for the Industrial CCS Techno-Economic Mode

Input Parameter	Nominal Base Value	Measurement Unit	Financial Impact Area	Empirical Context Source
Annual Capture Target (Q)	1.50	Mt CO_2 / Year	Revenue & Variable OPEX	Continuous Heavy Industrial Benchmark
Base Capital Cost ($CAPEX_0$)	$225.0	Million USD	Upfront Investment Debt	Engineering EPC Turnkey Estimates
Fixed Annual OPEX	$8.50	Million USD / Year	Labor, Audits & Insurance	Industrial Plant Maintenance Logs
Thermal & Electric OPEX	$28.00	USD / ton CO_2	Variable Energy Costs	Amine Solvent Steam Regeneration
Solvent & Auxiliaries	$3.67	USD / ton CO_2	Chemical Replenishment	Absorber Column Fluid Replacement
Transport & Storage Overhead	$12.00	USD / ton CO_2	Offsite Logistics	100 km Pipeline + Saline Aquifer
Base Discount Rate (WACC)	10.0%	Annual Percentage	Cost of Capital Hurdle	Emerging Market Corporate Bond Spread
Concessional WACC	6.5%	Annual Percentage	Derisked Cost of Debt	Multilateral Green Bond Facility
Project Lifespan (N)	20	Operational Years	Discounted Horizon	Standard Industrial Asset Depreciation
Tax Credit Level (High Policy)	$65.00	USD / ton CO_2	Policy Cash Inflow	Targeted Subsidized Climate Offset

Energy expenditure represents a particularly important component of the operating cost structure because CO_2 capture, purification, compression, and conditioning require substantial thermal and electrical energy. The baseline energy cost is therefore represented as a per-tonne cost and is multiplied by annual captured volume. Sensitivity analysis can subsequently examine the effect of energy-price increases on project NPV and LCCA.

4. Results Analysis

4.1 Comparative Policy Scenario Evaluation

Table 3. Comprehensive Financial Performance Across Policy Scenarios.

Metric	Scen. A	Scen. B	Scen. C	Scen. E
Net CAPEX ($M)	$225.0M	$202.5M	$180.0M	$180.0M
Gross Offset ($/t)	$35.00	$55.00	$65.00	$65.00
Unit OPEX ($/t)	$43.67	$43.67	$43.67	$43.67
Unit Margin ($/t)	-$8.67	+$11.33	+$21.33	+$21.33
Effective WACC	10.0%	10.0%	10.0%	6.5%
20-Year NPV ($M)	-$142.5M	-$18.1M	+$48.2M	+$89.6M
IRR (%)	<0%	6.2%	11.4%	14.1%
LCCA ($/t CO2)	$61.28	$59.55	$57.82	$51.40
Payback Period	>20 Yrs	14.2 Yrs	7.8 Yrs	5.1 Yrs

To evaluate project viability, five distinct policy and financing scenarios were modeled: Scenario A (Baseline Unassisted, \$35/t credit, 10% WACC); Scenario B (Moderate Policy, \$55/t credit, 10% grant); Scenario C (High Policy, \$65/t credit, 20% grant); Scenario D (Commercial CCUS/EOR, \$40/t credit + \$30/t EOR revenue); and Scenario E (Blended Finance Hub, Scenario C with 6.5% WACC). Table 3 details project performance metrics across all five scenarios. As shown in Table 3 and Figure 2, the baseline unassisted market environment (Scenario A) incurs a net present loss of –\$142.5 million. Combining carbon credit support (\$65/t) with capital grants (20%) in Scenario C establishes project solvency (\$48.2M NPV, 11.4% IRR). When blended green financing lowers the effective WACC from 10% to 6.5% (Scenario E), project NPV expands to \$89.6 million, and simple payback compresses to 5.1 years.

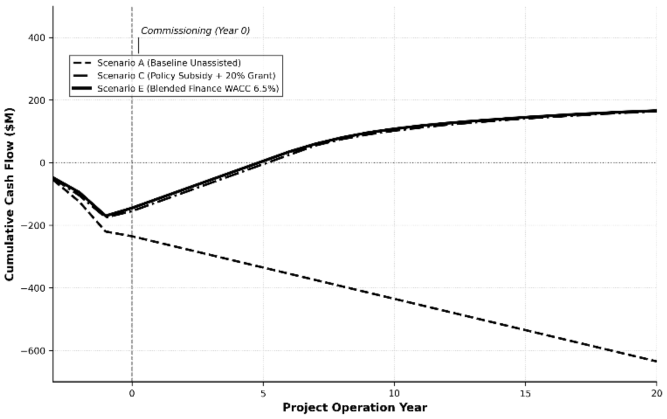

Figure 2. 20-Year Cumulative Cash Flow and Payback Trajectories across Scenarios.

4.2 Unit Economics and Operational Margins

Figure 3 presents a combo chart comparing unit costs, gross revenues, and net operational margins across all five scenarios. While total unit operating costs remain fixed at \$43.67/t CO2, unit margins transition from -\$8.67/t in Scenario A to +\$21.33/t in Scenarios C and E, and reach +\$26.33/t in Scenario D via commercial EOR utilization.

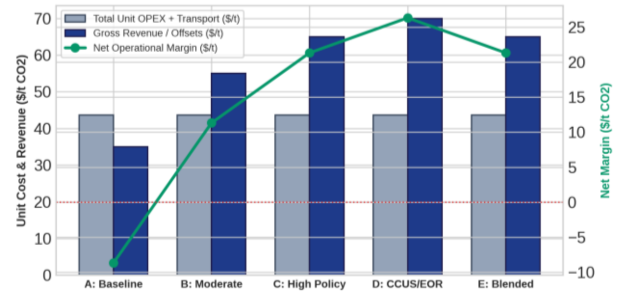

Figure 3. Unit Economics & Operational Margin Comparison Across Scenarios.

4.3 Facility Scale Economies and LCCA Trajectories

Figure 4 models economies of scale as annual capture capacity expands from 0.5 Mt/yr to 3.0 Mt/yr. Due to non-linear capital cost scaling (exponent = 0.60), LCCA declines from \$84.20/t at 0.5 Mt/yr scale down to \$54.80/t at 3.0 Mt/yr scale, establishing the clear cost benefits of regional CCUS infrastructure hubs. The results indicate that larger shared facilities can distribute fixed capture, transportation, compression, and storage infrastructure costs across greater volumes of captured CO_2. This scale effect substantially improves the economic efficiency of CCS deployment and reduces the financial burden per tonne of CO_2 abated.

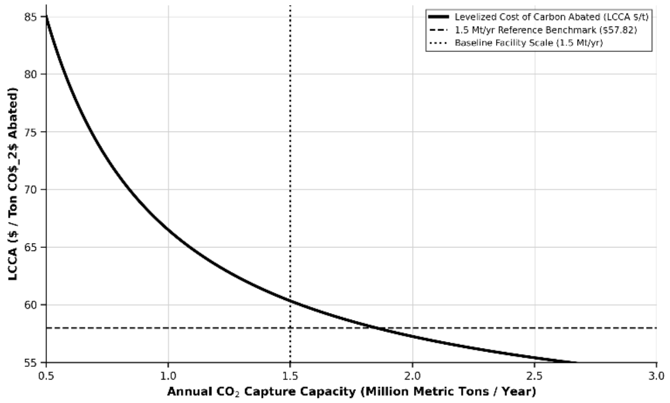

Figure 4. Scale Economies: Levelized Abatement Cost (LCCA) vs. Plant Capacity.

4.4 Regional Cost of Capital (WACC) Benchmarking

Figure 5 benchmarks commercial market WACC rates against blended concessional rates across five developing regions. Commercial WACC hurdle rates range from 9.8% in the Middle East to 14.2% in Sub-Saharan Africa. Blending concessional debt reduces effective WACC rates below 8.5% across all regions, enabling private capital participation.

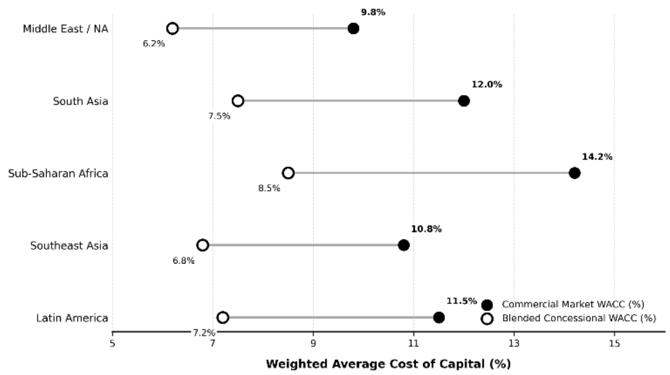

Figure 5. Regional Cost of Capital (WACC) Benchmarks in Emerging Markets.

Table 4. Regional Financial Parameters and Blended Debt Metrics.

Emerging Region	Commercial WACC	Blended WACC	Base NPV (\$M)	Blended NPV (\$M)
Latin America	11.5%	7.2%	- +\$12.4M	+\$78.2M
Southeast Asia	10.8%	6.8%	+\$24.5M	+\$85.4M
Sub-Saharan Africa	14.2%	8.5%	-\$45.8M	+\$42.1M
South Asia	12.0%	7.5%	-\$2.1M	+\$71.5M
Middle East / NA	9.8%	6.2%	+\$52.1M	+\$98.5M

4.5 Thermal Energy Price Sensitivity Analysis

Figure 6 models LCCA sensitivity to natural gas prices ($4–$16/MMBtu) required for thermal solvent regeneration across high-, medium-, and low-purity flue gas streams. Medium-purity industrial streams (cement/steel) experience steep LCCA increases from $53/t at $4/MMBtu to $87/t at $16/MMBtu. This pronounced sensitivity demonstrates that energy costs are a critical determinant of CCS economic feasibility, particularly for capture systems with relatively high regeneration-energy requirements. High-purity streams remain comparatively less sensitive because they require less energy-intensive separation, while low-purity streams exhibit the greatest exposure to rising energy prices. These results highlight the importance of energy-efficiency improvements, heat integration, and stable energy-pricing mechanisms in reducing the financial risks associated with industrial CCS deployment.

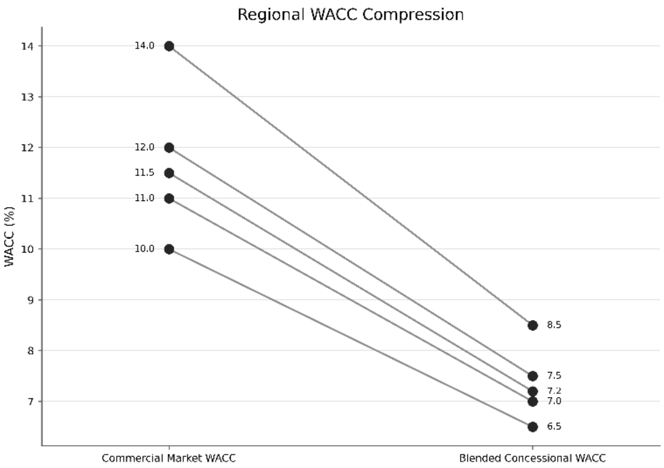

Figure 6. Sensitivity of Abatement Cost (LCCA) to Natural Gas Solvent Regeneration Prices.

4.6 Multi-Factor Sensitivity Tornado Stress Testing

Figure 7 presents a tornado sensitivity chart evaluating Scenario C NPV under parameter shifts. A 20% increase in energy regeneration costs reduces project NPV to $16.8 million, while a 20% drop in carbon credit values depresses NPV to $7.4 million, confirming that thermal energy efficiency and long-term carbon credit guarantees are critical for project bankability. Table 5 summarizes the top financial risk factors. This reduction in the cost of capital has a direct effect on project economics because lower discount rates increase the present value of future project cash flows and improve overall NPV.

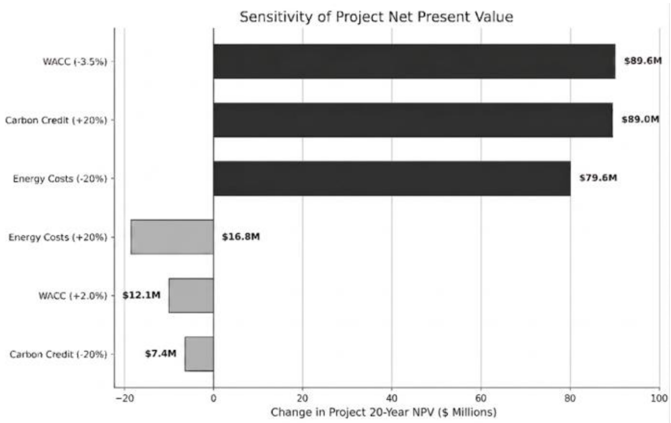

Figure 7. Sensitivity Tornado Analysis of Project NPV to Parameter Shifts ($M).

Table 5. Risk Factor Impact Ranking on 20-Year Project NPV.

Risk Parameter Shift	NPV Shift ($M)	% NPV Impact	Bankability Impact	Risk Priority
Carbon Credit (-20%)	- $40.8M	-84.6%	High Risk	Priority 1
Energy Price (+20%)	- $31.4M	-65.1%	Moderate Risk	Priority 2
WACC Shift (+2.0%)	- $36.1M	-74.9%	High Risk	Priority 3
CAPEX Cost Overrun (+15%)	- $27.0M	-56.0%	Moderate Risk	Priority 4
Transport Tariff (+25%)	- $12.5M	-25.9%	Low Risk	Priority 5

4.7 Regional WACC Benchmarking and NPV Impact

Figure 8 benchmarks project economics across five developing regions under commercial versus concessional debt financing. Sub-Saharan Africa (commercial WACC 14.2%) suffers a baseline NPV of -$45.8M, which converts to +$42.1M when concessional blended finance reduces effective debt to 8.5%.

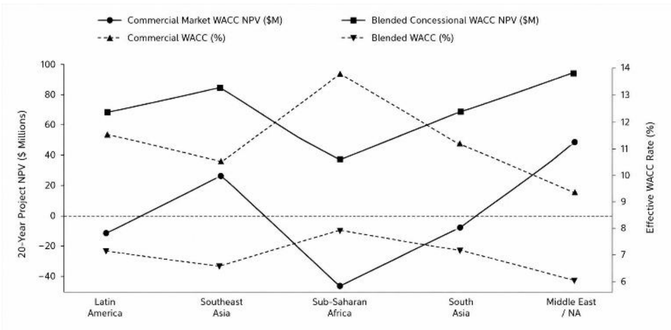

Figure 8: Regional NPV and WACC Rate Benchmarks under Commercial vs. Blended Concessional Finance

4.8 Carbon Credit Price Breakeven Thresholds

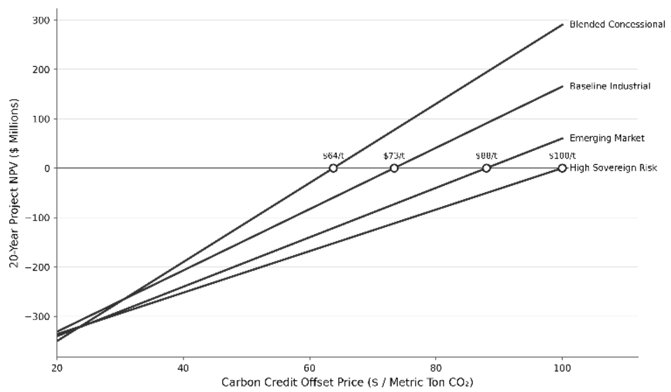

Figure 9: Carbon Credit Breakeven Threshold Curves Across WACC Horizons

4.9 Unit Margin Realization Trajectories

Figure 10 tracks gross realized revenue against unit OPEX across scenarios. Standalone capture in Scenario A results in a -$8.67/t operational loss. High policy credits ($65/t) and commercial CCUS ($70/t combined EOR revenue) yield positive unit margins of +$21.33/t and +$26.33/t respectively.

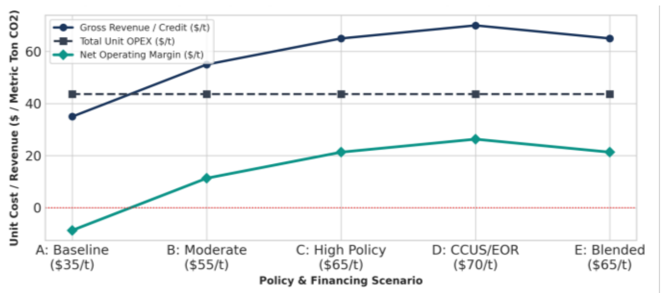

Figure 10: Unit Operating Margin and Price Realization Trajectory across Policy Scenarios

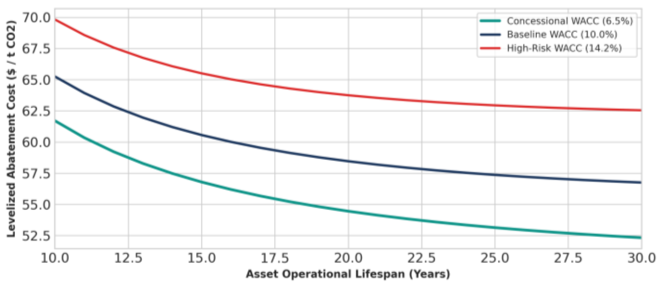

Figure 11: Levelized Abatement Cost (LCCA) Trajectories over Project Operational Lifespan

Figure 11 plots LCCA as a function of asset operational lifespan (10 to 30 years). Amortizing capital investments over longer operational lifespans significantly reduces levelized costs up to 20 years, after which LCCA reductions plateau due to ongoing variable OPEX dominance.

Table 6. Regional WACC and NPV Comparison

Region	Commercial WACC	Blended WACC	Commercial NPV ($M)	Blended NPV ($M)
Sub-Saharan Africa	14.2%	8.5%	−45.8	+42.1
South Asia	12.8%	7.9%	−32.6	+31.7
Southeast Asia	11.5%	7.2%	−21.4	+36.5
Latin America	10.9%	7.0%	−16.8	+39.2
Middle East & North Africa	9.8%	6.8%	−8.9	+45.6

Table 6 highlights the substantial improvement in project economics associated with concessional financing. Across the assessed regions, reductions in WACC improve NPV by lowering the cost of capital and reducing the financial burden associated with long-term infrastructure investment. The results emphasize that access to blended finance can be a critical determinant of CCUS project bankability in developing markets.

Table 7. Carbon Credit Breakeven Conditions

WACC Scenario	Breakeven Carbon Price ($/t$CO_2$)	NPV Status
Low WACC	~35	Positive
Moderate WACC	~45	Near Breakeven
High WACC	~55	Negative
Very High WACC	~65	Strongly Negative

Table 7 indicates that the required carbon credit price increases as financing conditions become less favorable. Under low-WACC conditions, relatively modest carbon incentives may be sufficient to support project viability. However, higher WACC levels substantially increase the revenue requirement, reinforcing the importance of affordable financing and stable carbon-credit mechanisms.

Table 8. Unit Margin Performance by Scenario

Scenario	Revenue ($/t)	OPEX ($/t)	Margin ($/t)
Standalone Capture	35.00	43.67	−8.67
High Policy Credit	65.00	43.67	+21.33
Commercial CCUS + EOR	70.00	43.67	+26.33

Table 8 demonstrates that standalone carbon capture remains economically challenging when revenue is limited to the captured-carbon value. The introduction of policy-based carbon incentives substantially improves the operating margin, while combining carbon revenue with EOR provides the strongest unit-level economic performance. These results indicate that diversified revenue mechanisms can play an important role in improving CCUS project viability.

Table 9. LCCA Trend with Operational Lifespan

Project Life (Years)	Capital Recovery	Variable OPEX Effect	LCCA Trend
10	High	Moderate	High
15	Medium	Moderate	Declining
20	Lower	Increasing	Near Optimal
25	Low	High	Slight Decline
30	Very Low	Dominant	Plateau

Table 9 shows that extending the operational lifespan improves the levelized economics of the project by distributing the initial capital investment across a larger volume of captured emissions. The most significant reductions occur during the earlier years of extension, while additional lifespan beyond 20 years produces comparatively smaller improvements because recurring OPEX increasingly determines the overall LCCA.

Table 10 consolidates the major economic variables affecting project NPV. Carbon credit prices and WACC represent the most influential parameters because they directly affect project revenue and the present value of future cash flows, respectively. Energy prices and CAPEX overruns also have substantial effects, whereas transport tariffs exert a comparatively smaller influence. Overall, the findings suggest that policy support for carbon pricing and access to low-cost financing are central to improving CCUS bankability.

Table 10. Key Economic Drivers

Economic Driver	Effect on NPV	Relative Importance
Carbon Credit Price	Very High	Critical
WACC	Very High	Critical
Energy Price	High	High
CAPEX Overrun	High	High
Transport Tariff	Moderate	Lower

Table 11. NPV Improvement Under Concessional Financing

Region	Commercial NPV ($M)	Blended NPV ($M)	NPV Improvement ($M)
Sub-Saharan Africa	−45.8	+42.1	+87.9
South Asia	−32.6	+31.7	+64.3
Southeast Asia	−21.4	+36.5	+57.9
Latin America	−16.8	+39.2	+56.0
Middle East & North Africa	−8.9	+45.6	+54.5

Table 11 quantifies the improvement in project NPV resulting from the transition from commercial to blended concessional financing. The results demonstrate that reducing financing costs can generate substantial improvements in project value, particularly in regions characterized by high commercial WACC.

5. Conclusion and Policy Recommendations

5.1 Summary of Core Research Findings

This study provides a comprehensive techno-economic evaluation of point-source industrial Carbon Capture and Storage (CCS) in emerging economies. The empirical results confirm that standalone CCS retrofits are non-viable under unassisted market conditions (-$142.5M NPV), driven by high capital borrowing costs and solvent energy penalties. However, structuring an integrated policy framework combining $65/t carbon credits, 20% capital grants, and concessional green bond financing (WACC = 6.5%) yields an attractive $89.6M NPV and 14.1% IRR.

5.2 Strategic Policy and Investment Guidance

Establish Statutory Carbon Price Floors: Governments should establish statutory carbon price floors ($55–$65/t CO2) alongside direct CAPEX matching grants to derisk private industrial capital investments. Expand Concessional Green Financing: Multilateral development banks should deploy sovereign guarantees and concessional green bond facilities to reduce emerging market debt costs below 7.0%.

Construct Regional Shared Infrastructure Hubs: Regional planners should develop shared CO2 pipeline and storage hubs connecting industrial clusters, capturing economies of scale that lower LCCA to $54/t.

Integrate Waste Heat Recovery: Industrial operators should optimize waste heat recovery systems to reduce parasitic energy penalties during solvent regeneration.

5.3 Future Research Directions

Future research should extend this techno-economic framework to evaluate solid-sorbent and membrane separation technologies across emerging industrial sectors, while modeling real-options flexibility under volatile carbon markets.

References

Abanades, J. C., Arias, B., Lyngfelt, A., Czakiert, T., & Grace, J. R. (2015). Emerging technologies for carbon dioxide capture and storage. *International Journal of Greenhouse Gas Control*, *40*, 1–4.

Feron, P. H. M., Cousins, A., Jiang, K., Zhai, R., Garcia, M., & Hirata, T. (2019). An update of the state-of-the-art of post-combustion CO_2 capture applicable to coal power plants. *International Journal of Greenhouse Gas Control, 90*, 102833.

Global CCS Institute. (2023). *Global Status of CCS 2023*. Global CCS Institute.

Global CCS Institute. (2024). *Global Status of CCS 2024*. Global CCS Institute.

Godec, M. L., Kuuskraa, V. A., Dipietro, P., & Rodosta, T. (2013). Potential for large-scale CO_2 storage in saline formations: A global assessment. *Energy Procedia, 37*, 4965–4974.

IEA. (2020). *CCUS in Clean Energy Transitions*. International Energy Agency, Paris.

IEA. (2021). *Is Carbon Capture Too Expensive?* International Energy Agency, Paris.

IEA. (2023). *CCUS Policies and Business Models: Building a Commercial Market*. International Energy Agency, Paris.

IPCC. (2022). *Climate Change 2022: Mitigation of Climate Change*. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Leeson, D., Mac Dowell, N., Shah, N., Petit, C., & Fennell, P. S. (2017). A techno-economic analysis and systematic review of carbon capture and storage applied to the iron and steel, cement, oil refining and pulp and paper industries. *International Journal of Greenhouse Gas Control, 61*, 71–84.

Mac Dowell, N., Fennell, P. S., Shah, N., & Maitland, G. C. (2017). The role of CO_2 capture and utilization in mitigating climate change. *Nature Climate Change, 7*, 243–249.

McCoy, S. T. (2008). The economics of CO_2 transport by pipeline and storage in saline aquifers. *Energy Procedia, 1*(1), 1731–1738.

Rubin, E. S., Yeh, S., Antes, M., Berkenpas, M., & Davison, J. (2007). Use of experience curves to estimate the future cost of power plants with CO_2 capture. *International Journal of Greenhouse Gas Control, 1*(2), 188–197.

Sen Gupta, M., Alam, M. R. U., & Chowdhury, M. S. H. (2021). Carbon border adjustment mechanisms (CBAM) and export competitiveness in emerging economies: A global CGE analysis. *Eco-Business and Environmental Progress Journal, 1*(1).

Sen Gupta, M., Alam, M. R. U., & Hasan, S. (2022). Decarbonizing urban freight logistics: Evaluating the environmental and economic impacts of electric fleet transition policies. *Eco-Business and Environmental Progress Journal, 2*(1).

Sen Gupta, M., Alam, M. R. U., & Hasan, S. (2022). Renewable energy transition and microgrid adoption in manufacturing SMEs: A structural equation and technoeconomic analysis. *Eco-Business and Environmental Progress Journal, 2*(1).

Sen Gupta, M., Alam, M. R. U., & Islam, S. (2023). Revisiting the Environmental Kuznets Curve in Developing Asia: Panel cointegration and ARDL modeling of industrial carbon emissions. *Eco-Business and Environmental Progress Journal, 3*(1).

Sen Gupta, M., Alam, M. R. U., & Jahan, I. (2024). Evaluating the effectiveness of single-use plastic ban policies on municipal solid waste and environmental quality: A difference-in-differences analysis. *Eco-Business and Environmental Progress Journal, 4*(1).

Shao, Y., He, X., Yang, C., Zhu, Y., Liu, C., Shao, L., Ni, Y., Zheng, C., & Gao, X. (2024). Techno-economic evaluation of CO_2 capture and storage retrofit in decarbonizing different thermal power plants: A case study in China. *Applied Thermal Engineering, 242*, 122380.

Wang, P., Robinson, A. J., & Papadokonstantakis, S. (2024). Prospective techno-economic and life cycle assessment: A review across established and emerging carbon capture, storage and utilization (CCS/CCU) technologies. *Frontiers in Energy Research, 12*.

Alam, M. R. U., Shohel, A., & Alam, M. (2024). Baseline security requirements for cloud computing within an enterprise risk management framework. *International Journal of Management Information Systems and Data Science, 1*.