

# CARBON CAPTURE, UTILIZATION AND STORAGE IN PETROLEUM OPERATIONS: FEASIBILITY AND RISKS

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## Abstract

The technical performance, economic viability, and risks of any particular project are all important to the deployment of carbon capture, utilisation, and storage (CCUS), a technology that is increasingly seen as one of the main options to reduce carbon dioxide (CO<sub>2</sub>) emissions from operations in the petroleum sector. The feasibility and risk of CCUS technology were evaluated for onshore and offshore oil fields, gas processing plants, refineries, and enhanced oil recovery projects through quantitative comparative and analytical assessments. The technical, economic, geological, and risk-related indicators were evaluated, and descriptive statistics, one-way analysis of variance, Welch's ANOVA, Pearson correlation, and multiple linear regression were performed. The average technical feasibility score was 3.31 on a five-point scale, with a mean CO<sub>2</sub> capture efficiency of 90.51%. The technical feasibility did not differ significantly between the petroleum operation types ( $p = 0.942$ ), but the economic feasibility did ( $p = 0.006$ ), and enhanced oil recovery projects performed comparatively well. There was also significant variation in overall risk by operation type ( $p < 0.001$ ), with offshore oil-field operations being the riskiest. The value of the carbon credit was positively correlated with the project net present value ( $r = 0.530$ ,  $p < 0.001$ ), and the energy penalty was negatively correlated with the technical feasibility ( $r = -0.576$ ,  $p < 0.001$ ). Multiple regression accounted for 68.3% of the variance in project NPV, with the carbon-credit value, total CCUS cost, and capital expenditure as significant predictors. Technically, CCUS seems viable for petroleum operations, but the economics and operations of the project depend on the project configuration, cost structure, policy incentives, and risk management conditions.

## 1. Introduction

Carbon capture, utilisation and storage (CCUS) is a key technological option for reducing carbon dioxide emissions from the energy-intensive sectors such as petroleum exploration,

production, processing and refining. Greenhouse gas emissions from petroleum operations are closely linked to large emissions from fuel combustion, gas processing, flaring, energy-

intensive refining, and other energy-intensive operations. CCUS provides a tool for CO<sub>2</sub> separation from industrial gas streams, transport to appropriate sites, use for valuable purposes and underground storage [1, 2]. In the petroleum industry, depleted oil and gas reservoirs and deep saline aquifers could serve as possible storage sites, and captured CO<sub>2</sub> could be utilised for EOR operations. The opportunity these applications present is to lower the carbon intensity of petroleum production by leveraging existing geological knowledge, subsurface infrastructure, and expertise. However, the widespread adoption will be contingent upon the technical performance, geological suitability, project economics, infrastructure needs, regulatory environment, and the security of long-term storage [3, 4].

There are several interrelated technical and economic considerations that impact the viability of CCUS in petroleum operations. Technical feasibility can vary depending on the project's capture efficiency, CO<sub>2</sub> availability, reservoir injectivity, storage capacity, injection rate, energy requirements, and transport distance. At the same time, the capital expenses of implementing CCUS are substantial, with capture facilities, compressor stations, pipelines, injection wells, monitoring, and storage sites all needing to be built [5, 6]. The cost of transporting and storing one tonne of CO<sub>2</sub> will also impact on the profitability of a project, as will the energy costs. Carbon credit revenues and even future revenues from CO<sub>2</sub> utilisation can have a positive effect on company profit, particularly if captured CO<sub>2</sub> can be used to enhance oil recovery. But in the case of complex transportation and storage systems, low carbon pricing systems and high capital costs, economically viable projects with low capital costs may not be technically viable. Hence, two criteria (engineering and economic) have to be considered when evaluating the feasibility of CCUS, rather than one [7, 8].

In addition to feasibility, there are several operational, geological, environmental, regulatory, and social risks that need to be taken into account when planning and implementing a CCUS

project. These possible issues include uncertainty about the behaviour of the wells, migration of CO<sub>2</sub> into unintended areas, pipeline incidents, well integrity failure, uncertainty about the long-term storage behaviour, public acceptance and regulatory liability. The risks may vary greatly between types of petroleum operations, such as onshore and offshore operations, and among types of geological storage. Thus, it is important to have an integrated quantitative assessment to determine the factors that influence project feasibility and risk. In the current study, the technical and economic feasibility, and the multifaceted risk profile of CCUS applications are therefore evaluated in major petroleum operations. The analysis also explores differences between operation types, correlations between key technical and economic variables and the main drivers of project NPV, which are presented in a structured way to help to understand the conditions that could facilitate safe and economically viable deployment of CCUS [9, 10].

## 2. Methodology

### 2.1 Research Design

The study used a quantitative comparative and analytical research design conducted at Mehran University of Engineering and Technology, SZAB Campus, Khairpur Mir's, Sindh, Pakistan to assess the technical viability, economic feasibility, and risks involved with carbon capture, utilization, and storage (CCUS) solutions in petroleum applications. The methodological approach was designed to enable the systematic comparison of the major applications in the petroleum sector: onshore oil fields, offshore oil fields, gas processing facilities, refineries, and enhanced oil recovery. The design focused on measurable project-level features and the statistical assessment of differences, associations, and predictors relevant to the implementation of CCUS.

### 2.2 Study Variables and Measurement Framework

Variables included in the study as technical, economic, geological, operational, and risk variables were relevant to the deployment of

CCUS. Technical variables considered were carbon dioxide stream availability, CO<sub>2</sub> capture efficiency, annual CO<sub>2</sub> capture volume, transportation distance, storage depth, reservoir injectivity, estimated storage capacity, injection rate, and energy penalty. The economic parameters considered are capital expenditure, annual operating expenditure, transportation cost, storage cost, total CCUS cost/tonne of CO<sub>2</sub>, carbon-credit value and project NPV. Risk-related variables were well-integrity risk, induced-seismicity risk, pipeline risk, regulatory risk, social-acceptance risk and estimated annual leakage probability. Multidimensional project characteristics were summarised and analyzed in terms of composite technical feasibility, economic feasibility and overall risk scores.

### 2.3 Assessment of Technical Feasibility

Operational and subsurface parameters affecting a petroleum facility's ability to capture, transport, inject, store, or utilise carbon dioxide were considered to assess technical feasibility. Capture efficiency was defined as the percentage of available CO<sub>2</sub> removed from the emission stream, and annual captured CO<sub>2</sub> was the amount available for transport and injection. The feasibility assessment of geological storage was conducted based on storage depth, reservoir injectivity, estimated storage capacity, and injection rate. Energy penalty has been added as a metric for the extra energy required for capture and compression, and for associated CCUS processes. These parameters were combined into a standardised technical feasibility score ranging from 1 to 5, with higher scores indicating greater technical suitability of the CCUS implementation.

### 2.4 Economic Feasibility Assessment

The project cost indicators and the long-term financial performance indicators were used to assess economic feasibility. The capital expenditure is the initial investment required for the capture system, compression plant, transport facilities, injection equipment, and project development activities. In contrast, annual

operating expenditure covers the costs of operating and maintaining the capture system. The costs of transport and geological storage were included in the total CCUS costs and stated per tonne of CO<sub>2</sub>. Project net present value was considered the most important long-term financial parameter, and the carbon-credit value was added to account for the potential effects of policy- or market-based incentives. The project-level economic feasibility score (1 to 5) was summarised to capture project economic performance. The project-level economic feasibility score (1 to 5) was used to summarise the project's economic performance.

### 2.5 Risk Assessment Framework

The principal operational, geological, environmental, regulatory, and social risks associated with CCUS implementation were analyzed using a multidimensional risk assessment framework. Well-integrity risk was the risk of leakage or mechanical failure from injection and legacy wells, and induced-seismicity risk was the risk of pressure-related subsurface disturbances resulting from CO<sub>2</sub> injection. Pipeline risk was evaluated based on transportation distance and operational complexity, and regulatory risk was evaluated based on uncertainties surrounding permits, monitoring, liability, and long-term storage governance. There was an overall perception of social acceptance risk as a potential stakeholder concern and of public resistance to CCUS infrastructure. These individual risk components (along with estimated leakage probability) were summed and combined with an overall risk score (1-5), after which the risk was classified as low, moderate, or high.

### 2.6 Statistical Analysis

Data were analysed statistically using procedures appropriate to the available data in IBM SPSS Statistics. Means, standard deviations, minimum and maximum values were used to summarise continuous variables and frequencies and proportions were used for categorical variables. One-way analysis of variance was used to evaluate differences in technical feasibility, economic

feasibility, overall risk, and project net present value by petroleum operation category. Homogeneity of variance was assessed using Levene's test, and Welch's analysis of variance was used when this assumption was not met. Tukey's honestly significant difference test was used for post-hoc comparisons where appropriate. Pearson's correlation analysis was used to examine the relationships among technical, economic, and risk variables. A multiple linear regression analysis was used to evaluate the independent contribution of each element of the carbon-credit value, total cost of CCUS, and capital expenditure to project NPV. The statistical significance was determined at the 2-sided alpha level of 0.05, and regression

diagnostics performed included residual normality, multicollinearity, and autocorrelation.

### 3. Results

#### 3.1 Descriptive Characteristics of CCUS Projects

The descriptive statistics for the principal technical, economic, and risk-related variables are presented in Table 1. The mean CO<sub>2</sub> capture efficiency was 90.51%, while the average captured CO<sub>2</sub> volume was 2.47 Mt per year. The mean total CCUS cost was USD 68.31 per tonne of CO<sub>2</sub>, whereas the average project net present value was USD −969.73 million. The mean overall risk score was 2.57, while the mean technical and economic feasibility scores were 3.31 and 1.53, respectively.

**Table 1: Descriptive Statistics of Major CCUS Variables**

| Variable                                 | Mean    | SD     | Minimum  | Maximum |
|------------------------------------------|---------|--------|----------|---------|
| CO <sub>2</sub> stream (Mt/year)         | 2.73    | 1.43   | 0.53     | 4.99    |
| Capture efficiency (%)                   | 90.51   | 3.24   | 82.47    | 98.00   |
| CO <sub>2</sub> captured (Mt/year)       | 2.47    | 1.29   | 0.44     | 4.55    |
| Transport distance (km)                  | 156.46  | 83.57  | 11.60    | 414.00  |
| Storage depth (m)                        | 2375.31 | 838.74 | 934.00   | 4153.00 |
| Energy penalty (%)                       | 12.54   | 3.63   | 5.03     | 19.84   |
| CAPEX (USD million)                      | 937.83  | 336.76 | 359.06   | 1594.20 |
| Annual OPEX (USD million)                | 67.81   | 18.65  | 32.90    | 105.03  |
| Total CCUS cost (USD/t CO <sub>2</sub> ) | 68.31   | 7.66   | 51.57    | 84.84   |
| Carbon credit (USD/t CO <sub>2</sub> )   | 56.19   | 20.77  | 21.06    | 94.66   |
| Project NPV (USD million)                | −969.73 | 637.98 | −3377.10 | 89.21   |
| Overall risk score                       | 2.57    | 0.34   | 1.74     | 3.44    |
| Technical feasibility score              | 3.31    | 0.38   | 2.53     | 4.07    |
| Economic feasibility score               | 1.53    | 0.62   | 1.00     | 3.45    |

#### 3.2 Feasibility Across Petroleum Operations

Mean technical feasibility scores were broadly similar across the five petroleum-operation categories, whereas economic feasibility varied more noticeably (Table 2). EOR projects

demonstrated the highest mean economic feasibility score (1.76), while onshore oil-field projects showed the lowest mean score (1.28). The comparative pattern of technical and economic feasibility is illustrated in Figure 1.

**Table 2: Mean Feasibility, Risk, and NPV According to Petroleum-Operation Type**

| Petroleum operation  | Technical feasibility | Economic feasibility | Overall risk | NPV (USD million) |
|----------------------|-----------------------|----------------------|--------------|-------------------|
| EOR project          | 3.33                  | 1.76                 | 2.48         | −738.38           |
| Gas processing plant | 3.30                  | 1.60                 | 2.52         | −867.15           |
| Offshore oil field   | 3.31                  | 1.40                 | 3.02         | −1100.66          |
| Onshore oil field    | 3.26                  | 1.28                 | 2.42         | −1149.67          |
| Refinery             | 3.34                  | 1.58                 | 2.48         | −1037.80          |

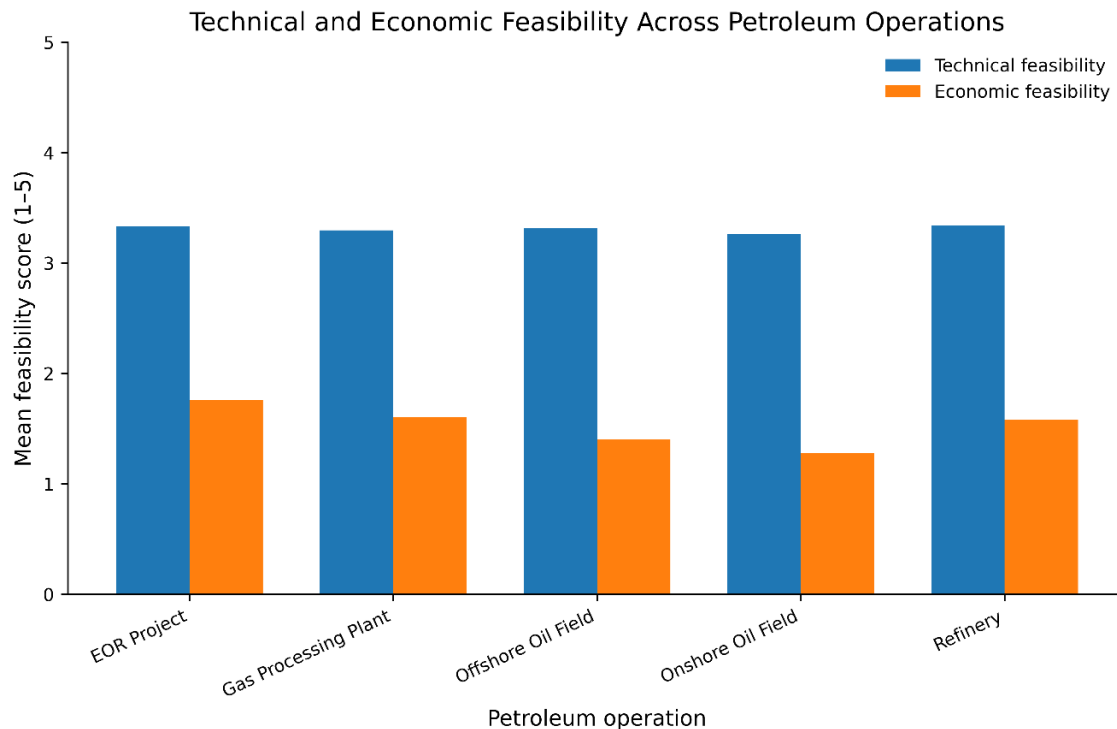


Figure 1: Technical and economic feasibility across petroleum operations.

### 3.3 Comparison of Technical and Economic Feasibility

The homogeneity-of-variance assumption for technical feasibility was satisfied, as Levene's test was not statistically significant ( $p = 0.457$ ). One-way analysis of variance showed no significant difference in technical feasibility among petroleum-operation categories,  $F(4,145) = 0.193$ ,  $p = 0.942$ . This result indicates that technical feasibility remained broadly comparable across the

evaluated petroleum operations. For economic feasibility, Levene's test was statistically significant ( $p = 0.032$ ), indicating unequal group variances. Welch's analysis of variance therefore was applied and demonstrated a significant difference among operation types, Welch's  $F(4,69.08) = 3.968$ ,  $p = 0.006$ . Post-hoc analysis showed that EOR projects had significantly higher economic feasibility than onshore oil-field projects (adjusted  $p = 0.006$ ).

Table 3: Comparison of Feasibility and Risk Outcomes Among Petroleum-Operation Types

| Outcome               | Statistical test | Test statistic       | p-value | Interpretation  |
|-----------------------|------------------|----------------------|---------|-----------------|
| Technical feasibility | One-way ANOVA    | $F(4,145) = 0.193$   | 0.942   | Not significant |
| Economic feasibility  | Welch's ANOVA    | $F(4,69.08) = 3.968$ | 0.006   | Significant     |
| Overall risk          | One-way ANOVA    | $F(4,145) = 23.065$  | <0.001  | Significant     |
| Project NPV           | One-way ANOVA    | $F(4,145) = 2.448$   | 0.049   | Significant     |

### 3.4 Comparison of Overall Risk

Overall risk differed significantly across petroleum-operation categories,  $F(4,145) = 23.065$ ,  $p < 0.001$ . Offshore oil-field projects had the highest mean risk score (3.02), whereas the remaining operation categories had mean scores

ranging from 2.42 to 2.52. Tukey post-hoc analysis showed that offshore oil-field projects had significantly higher overall risk than EOR projects, gas processing plants, onshore oil fields, and refineries, with all pairwise comparisons reaching

$p < 0.001$ . The difference in mean overall risk among operation types is shown in Figure 2.

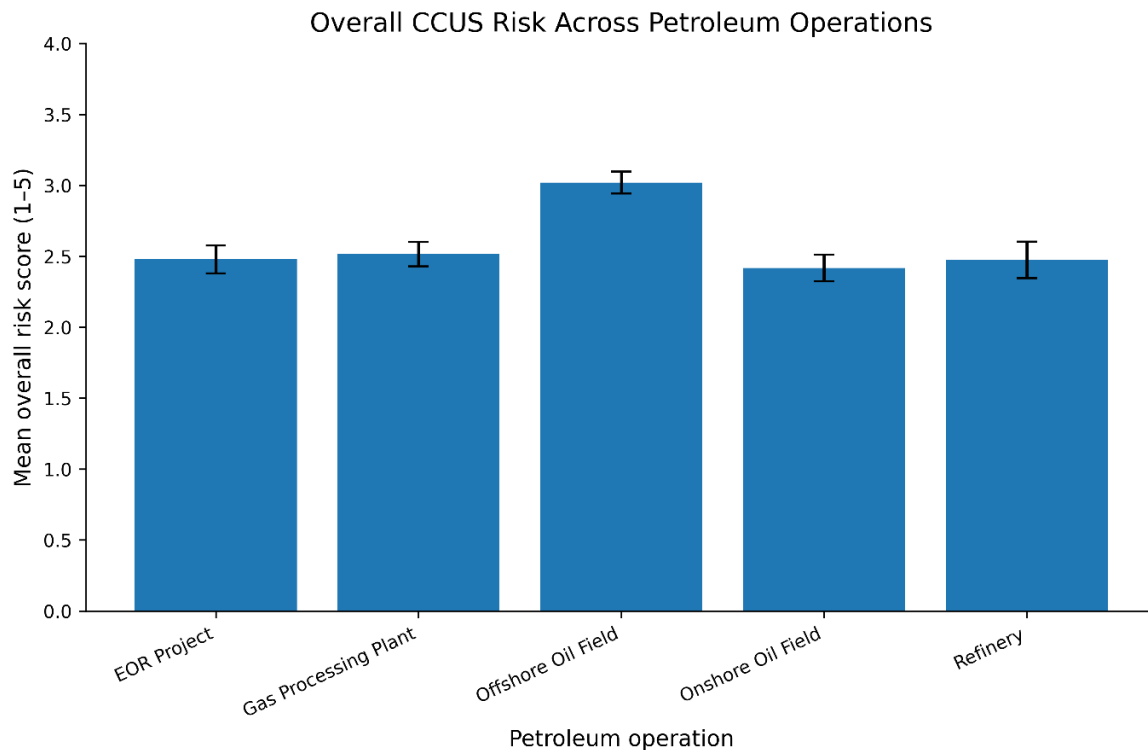


**Figure 2: Overall CCUS risk across petroleum operations.**

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### 3.5 Comparison of Project Net Present Value

Project net present value differed across petroleum-operation categories, with the omnibus one-way ANOVA reaching statistical significance,  $F(4,145) = 2.448$ ,  $p = 0.049$ . EOR projects demonstrated the least negative mean NPV at USD  $-738.38$  million, whereas onshore oil-field

projects had the most negative mean NPV at USD  $-1149.67$  million. However, none of the individual Tukey-adjusted pairwise comparisons remained statistically significant at the 0.05 level. The distribution of mean project NPV across operation types is presented in Figure 3.

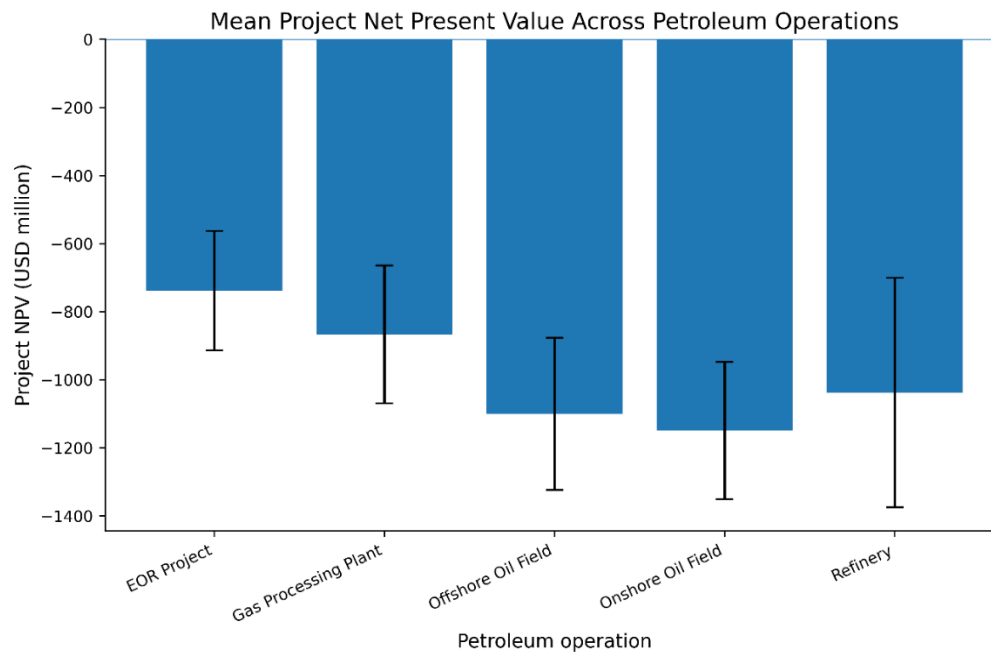


Figure 3: Mean project net present value across petroleum operations.

### 3.6 Correlation Analysis

Pearson correlation analysis identified several statistically significant relationships among technical, economic, and risk-related variables (Table 4). Carbon-credit value showed a moderate positive correlation with project NPV ( $r = 0.530$ ,  $p < 0.001$ ), whereas captured  $\text{CO}_2$  volume was negatively correlated with NPV ( $r = -0.501$ ,  $p < 0.001$ ). Energy penalty demonstrated a moderate-to-strong negative correlation with technical feasibility ( $r = -0.576$ ,  $p < 0.001$ ). Overall risk was

positively associated with transport distance ( $r = 0.414$ ,  $p < 0.001$ ), storage depth ( $r = 0.492$ ,  $p < 0.001$ ), and injection rate ( $r = 0.318$ ,  $p < 0.001$ ). Capture efficiency was not significantly correlated with technical feasibility ( $r = 0.044$ ,  $p = 0.593$ ), while total CCUS cost was not significantly correlated with project NPV in the unadjusted bivariate analysis ( $r = -0.105$ ,  $p = 0.201$ ). The direction and relative magnitude of these correlations are summarized visually in Figure 4.

Table 4: Pearson Correlations Among Selected CCUS Variables

| Variable pair                              | r      | p-value |
|--------------------------------------------|--------|---------|
| Carbon credit - Project NPV                | 0.530  | <0.001  |
| Total CCUS cost - Project NPV              | -0.105 | 0.201   |
| $\text{CO}_2$ captured - Project NPV       | -0.501 | <0.001  |
| Energy penalty - Technical feasibility     | -0.576 | <0.001  |
| Capture efficiency - Technical feasibility | 0.044  | 0.593   |
| Transport distance - Overall risk          | 0.414  | <0.001  |
| Storage depth - Overall risk               | 0.492  | <0.001  |
| Injection rate - Overall risk              | 0.318  | <0.001  |

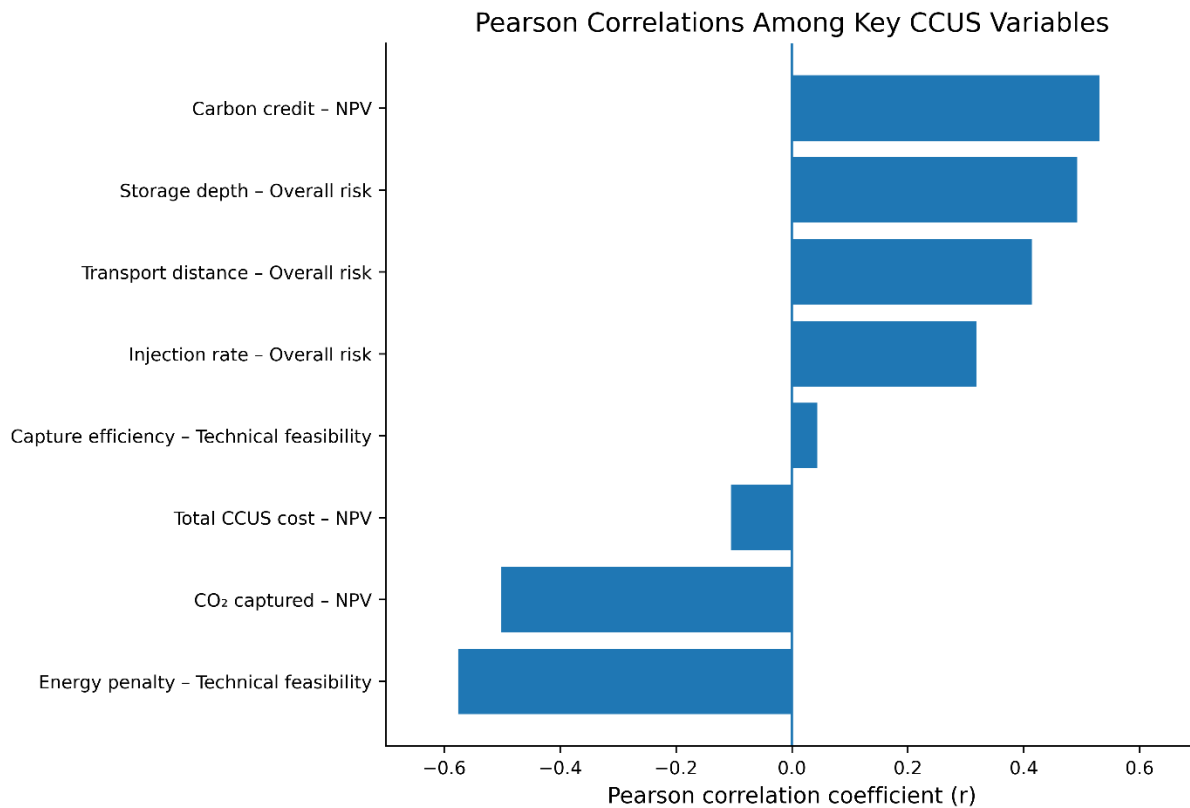


**Figure 4: Pearson correlation coefficients among key CCUS variables.**

### 3.7 Predictors of Project Net Present Value

Multiple linear regression was conducted to evaluate the independent effects of carbon-credit value, total CCUS cost, and capital expenditure on project NPV. The overall model was statistically significant,  $F(3,146) = 104.77$ ,  $p < 0.001$ , and explained 68.3% of the variance in project NPV ( $R^2 = 0.683$ ; adjusted  $R^2 = 0.676$ ). All three predictors were statistically significant (Table 5).

Carbon-credit value was positively associated with NPV ( $B = 20.27$ ,  $\beta = 0.660$ ,  $p < 0.001$ ), whereas total CCUS cost ( $B = -21.23$ ,  $\beta = -0.255$ ,  $p < 0.001$ ) and capital expenditure ( $B = -1.095$ ,  $\beta = -0.578$ ,  $p < 0.001$ ) were negatively associated with project NPV. The observed positive relationship between carbon-credit value and project NPV is further illustrated in Figure 5.

**Table 5: Multiple Linear Regression Predicting Project NPV**

| Predictor                                | B      | Standardized $\beta$ | p-value |
|------------------------------------------|--------|----------------------|---------|
| Constant                                 | 368.43 | —                    | —       |
| Carbon credit (USD/t CO <sub>2</sub> )   | 20.27  | 0.660                | <0.001  |
| Total CCUS cost (USD/t CO <sub>2</sub> ) | -21.23 | -0.255               | <0.001  |
| CAPEX (USD million)                      | -1.095 | -0.578               | <0.001  |

Model statistics:  $R^2 = 0.683$ ; adjusted  $R^2 = 0.676$ ;  $F(3,146) = 104.77$ ;  $p < 0.001$ .

Regression diagnostics indicated acceptable model performance. Variance inflation factors were close to 1, suggesting no substantial multicollinearity

among predictors. Residual normality was acceptable based on the Shapiro-Wilk test ( $p = 0.056$ ), while the Durbin-Watson statistic of

2.154 indicated no meaningful residual autocorrelation.

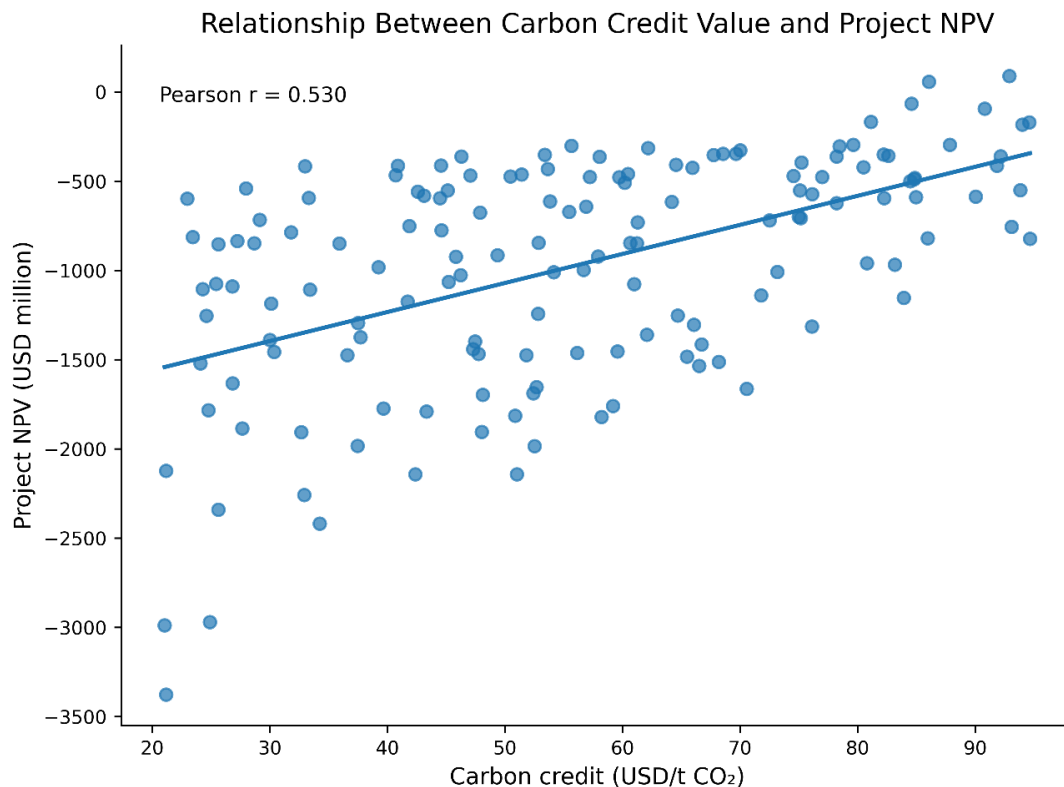


Figure 5. Relationship between carbon-credit value and project net present value.

#### 4. Discussion

The results show that carbon capture, utilisation, and storage (CCUS) can deliver high mean CO<sub>2</sub> capture efficiency and mostly similar technical feasibility scores for various petroleum projects, including those in the gas, liquids, and gas-to-liquid categories. There were no significant differences in technical feasibility between the different types of EOR projects, gas processing plants, offshore oil fields, onshore oil fields, or refineries, indicating that the primary technical requirements for CCUS can be met in a wide variety of petroleum-sector applications. The negative correlation between energy penalty and technical feasibility, however, underscores the importance of energy efficiency in assessing practical deployment potential. The technical viability of CCUS systems can be compromised by

additional energy requirements for capturing, compressing, transporting, and injecting the CO<sub>2</sub> stream, highlighting the importance of energy-efficient capture technologies and optimised process integration [11, 12].

Economic performance was a more limiting aspect of CCUS feasibility. Project economics were generally difficult, but EOR projects showed the highest overall mean economic feasibility and the lowest mean NPV. The results show large variations in economic viability among petroleum operation types, indicating that the economic potential of CCUS is highly dependent on the operational context and opportunities for CO<sub>2</sub> utilisation. The relative success of the EOR projects could be attributed to the additional economic benefit of using CO<sub>2</sub> in production. Furthermore, the carbon-credit value showed a

significant positive correlation with project NPV and was the strongest positive predictor in the regression model. However, total expenditure for CCUS (CCUS-C + CCUS-Capital) had a strong negative impact on NPV, indicating that economic viability requires project costs to be balanced by sufficient economic incentives or revenue-generating mechanisms [13, 14].

The results of the risk assessment revealed significant differences across categories of petroleum operations, particularly for offshore projects. The overall risk for offshore oil-field applications was considerably greater than for all other types of operations. This higher risk profile is aligned with the greater operational complexity of offshore infrastructure, longer transportation routes, difficult well access, and deep subsurface conditions. The overall risk scores are also positively correlated with transportation distance, storage depth and injection rate, further supporting the conclusion that project size and geological properties have a significant impact on the project risk profile of CCUS systems. The results show the need for careful characterisation of the site, well-integrity management, monitoring of the transportation system, and control of injection pressure in the design of large-scale storage projects, especially in an offshore environment [15, 16].

Together, the findings illustrate that the feasibility of CCUS for petroleum operations cannot be judged by capture efficiency or technical ability alone. A complete evaluation should consider the technical performance, project economic considerations, geological suitability, infrastructure needs, and multidimensional risk. The model revealed a significant portion of the variation in project NPV, further confirming the importance of carbon-credit incentives, the overall cost of CCUS, and capital expenditure in the financial outcome. Therefore, a successful rollout of CCUS in the petroleum industry will likely require the simultaneous optimisation of technology, cost reduction, risk management, and economic mechanisms. Hence, project-specific assessment is crucial: technically viable projects can be financially unattractive and operationally

risky if their cost structure is unfavourable or if storage conditions are complex.

## 5. Conclusion

This study shows that carbon capture, utilisation and storage (CCUS) is technically feasible, has significant potential for integration into many petroleum operations, and exhibits high capture performance and broadly similar technical feasibility across the various types of projects. Economic feasibility remains a significant barrier, though, because the project's outcomes are sensitive to the amount of capital spent, the overall cost of CCUS, and the potential for carbon-credit incentives. Offshore oil-field applications were the riskiest, and enhanced oil recovery projects had better economic results. The strong correlations between transport distance, storage depth, injection rate and overall risk further underscore the importance of the geological and infrastructural conditions for each project. Overall, the results suggest that a comprehensive assessment of technical, financial, and multidimensional operational and environmental risk is needed for successful CCUS deployment. The following implementation strategies should therefore focus on reducing costs, capture technologies that use energy efficiently, thorough characterisation of the storage sites, ongoing monitoring, and policy support. An integrated approach is crucial to making CCUS more economically viable and sustainable for decarbonisation of the petroleum sector.

## 6. Funding

Not applicable.

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