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Comparative Analysis of Life Cycle Cost and CO₂ Emissions in Offshore Oil Transport Systems

Dwi Retno Mulyaningsih^{1*}, Titi Sari Nurul Rachmawati², Wisnu Isvara³

¹ Fakultas Teknik, Program Magister Teknik Sipil, Universitas Indonesia, Salemba, Indonesia

^{2,3} Civil and Environmental Engineering Department, Universitas Indonesia, Salemba, Indonesia

*Corresponding Author: dwi.retno42@ui.ac.id

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ABSTRACT

This study evaluates the optimal offshore oil transportation system by comparing three alternatives: oil barge leasing, oil barge purchasing, and a pipeline-based permanent facility. An integrated analytical framework combining Life Cycle Cost (LCC), CO₂ emissions, and Multi-Criteria Decision Analysis (MCDA) was applied to assess economic, environmental, safety, and social performance. Cost estimation for the permanent facility was supported using QUE\$TOR software. The results show that although the permanent facility requires higher initial capital expenditure (CAPEX), it generates substantially lower operational expenditure (OPEX), leading to superior long-term cost efficiency. Quantitatively, the pipeline-based system reduces total LCC by approximately 30–35% compared with oil barging systems. In contrast, barging alternatives offer lower upfront costs but incur higher recurring expenses due to fuel consumption, vessel rental, and operational complexity. From an environmental perspective, the permanent facility significantly lowers CO₂ emissions by approximately 95–98%, mainly through reduced dependence on fossil fuel-based marine transportation. Safety analysis indicates that pipeline systems achieve up to 75% lower risk levels by eliminating hazardous offshore activities such as mooring, anchoring, and vessel transfer operations. In addition, the permanent facility creates lower social disturbance to coastal communities because of reduced operational intensity. The MCDA results consistently rank the permanent facility as the best-performing alternative across all evaluation criteria. These findings demonstrate that pipeline-based permanent facilities provide a more sustainable, safe, and economically viable solution for long-term offshore oil transportation, highlighting the importance of integrated decision-making frameworks in offshore infrastructure planning.



INTRODUCTION

The global energy industry, particularly the oil and gas sector, is currently facing increasingly complex multidimensional pressures, especially in achieving simultaneous operational efficiency and environmental impact reduction. Cost optimization can no longer be viewed partially in terms of short-term operational expenses but must encompass the entire asset life cycle through a Life Cycle Cost (LCC) approach, which includes Capital Expenditure (CAPEX), Operational Expenditure (OPEX), and decommissioning costs at the end of facility life (Ariyo et al., 2021). In this context, oil and gas companies are also confronted with global demands to reduce carbon dioxide (CO₂) emissions as part of commitments to climate change mitigation and sustainability agendas (Massarra et al., 2022). These pressures are further reinforced by international and national regulations requiring transparency and accountability in greenhouse gas emissions management. Therefore, decision-making in the design and selection of production facility systems must no longer focus solely on technical and economic aspects but must also comprehensively integrate environmental dimensions. In practice, failure to integrate these three aspects may lead to long-term inefficiencies, increased operational costs, and reputational risks for companies. Thus, an evaluation approach based on the integration of LCC and CO₂ emissions becomes highly relevant in the modern oil and gas industry. This reflects a paradigm shift toward a more holistic and sustainability-oriented project management approach.

In this context, the oil and gas industry is increasingly required to balance cost efficiency with environmental sustainability, while simultaneously addressing safety performance and social impact considerations. This multidimensional requirement necessitates the development of a unified analytical framework that integrates economic, environmental, safety, and social aspects to support more comprehensive and strategic decision-making.

In field operations, one of the primary challenges is the selection of an optimal oil transportation system, particularly between oil barging and permanent facilities such as pipelines. Oil barging systems generally offer high flexibility and relatively low CAPEX; however, they tend to incur higher OPEX due to dependence on fossil fuels, rental costs, and fluctuating operational factors (Altaf et al., 2022; Chen et al., 2023). In contrast, permanent facilities require substantial initial investment but offer long-term efficiency through operational stability and reduced recurring costs. Previous studies indicate that pipeline systems tend to be more energy-efficient and generate lower emissions compared to oil barging (Jimenez et al., 2023; Redutskiy & Balycheva, 2024). However, the decision-making process is far from straightforward, as it involves multiple interacting variables, including technical, economic, environmental, and operational risk factors. This complexity necessitates a more comprehensive and data-driven analytical approach. Therefore, a robust evaluation framework capable of accommodating multiple dimensions simultaneously is required. This serves as a fundamental basis for developing research oriented toward strategic decision-making.

Accordingly, this study adopts an integrated evaluation approach that simultaneously considers Life Cycle Cost (LCC), CO₂ emissions, safety risk, and social impact within a single decision-making framework, enabling a more holistic comparison between alternative oil transportation systems.



From an environmental perspective, CO₂ emissions serve as a key indicator in assessing the operational impact of oil and gas facilities on climate change. Oil barging systems are known to produce higher emissions due to diesel fuel consumption during transportation activities, including shipping, loading, and unloading processes (Adedipe & Shafiee, 2021; Torres & Niewöhner, 2023). Meanwhile, permanent facilities, although associated with significant carbon footprints during the construction phase, tend to be more efficient during long-term operations (Chen et al., 2023). The integration of Life Cycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA) has become increasingly important in evaluating trade-offs between economic costs and environmental impacts (Qiao et al., 2022). This integrated approach enables companies not only to optimize costs but also to minimize overall carbon footprints. Within the context of energy transition, such an approach is highly strategic as it supports global decarbonization targets. Therefore, LCC and CO₂-based analyses are critical instruments in promoting sustainability within the oil and gas industry. This also aligns with growing stakeholder demands for environmental transparency and accountability.

Beyond environmental considerations, safety and social dimensions also play critical roles in determining the overall feasibility and sustainability of offshore oil transportation systems, thereby reinforcing the need for an integrated multi-criteria evaluation framework.

Previous studies have developed various approaches to enhance operational efficiency and sustainability in the oil and gas industry. Modularization and process intensification in facility design have been shown to improve project efficiency while reducing both costs and emissions (Budna & Vižintin, 2023). Additionally, the implementation of Engineering, Procurement, Construction, and Installation (EPCI) models has proven effective in improving time and cost efficiency in project execution (Lu et al., 2024). On the other hand, decarbonization strategies, including the adoption of low-carbon technologies and energy efficiency measures, have also been widely discussed in the literature (Alrasheed, 2023). However, most of these studies remain partial and have not integrated technical, economic, and environmental aspects within a single comprehensive analytical framework. Furthermore, many studies are still simulation-based and lack application in complex real-world oil and gas field cases. This indicates clear limitations in the existing literature. Therefore, there is a need for research that addresses these gaps through a more integrative approach. Consequently, this study contributes to enriching the current body of knowledge.

Specifically, this study responds to the need for an integrative framework that combines multiple performance indicators into a single analytical structure to enhance the robustness of decision-making in offshore oil transportation projects.

Based on the literature review and state-of-the-art analysis, several significant research gaps can be identified. First, there is a lack of studies integrating Life Cycle Cost analysis, CO₂ emissions, and project management approaches such as EPCI within a single comprehensive framework. Second, there is no established quantitative indicator-based evaluation model specifically applied to offshore oil transportation projects in Indonesia. Third, limited research combines both quantitative and qualitative approaches in strategic decision-making, particularly through Multi-Criteria Decision Analysis (MCDA). Fourth, there is a scarcity of studies directly comparing oil barging and permanent facilities within active (brownfield) production environments. Fifth, there is insufficient



integration of cost, environmental, safety, and social aspects within a unified evaluation framework. These gaps indicate substantial opportunities for further research development. Therefore, this study is designed to address these limitations. As such, it occupies a clear position in scientific contribution.

The urgency of this research is further reinforced by increasing regulatory pressures and stakeholder demands for CO₂ emission reduction and operational efficiency improvement. Global commitments such as the Paris Agreement, along with national policies requiring greenhouse gas emissions reporting, compel companies to proactively manage their environmental impacts. In addition, the adoption of Environmental, Social, and Governance (ESG) principles in corporate performance evaluation increasingly drives the integration of sustainability aspects into business decision-making. International financial institutions and global investors now require low-carbon standards for funded projects. This creates additional pressure for companies to adopt more efficient and environmentally friendly facility designs. In this context, the selection of oil transportation systems becomes a strategic decision with long-term implications. Therefore, research that provides data-driven decision-making frameworks is critically important. Hence, the urgency of this study is both academic and practical.

This study offers novelty through the development of an integrated evaluation framework that combines Life Cycle Cost (LCC), CO₂ emissions, and Multi-Criteria Decision Analysis (MCDA) within a single analytical model. This approach enables a more comprehensive evaluation by simultaneously considering multiple criteria, including economic, environmental, safety, and social aspects. Additionally, this study integrates an EPCI-based project management approach within the context of permanent facility development. Another novelty lies in the application of this model to a real case study in Indonesian oil and gas fields, which remains relatively unexplored in previous research. Thus, this study contributes not only theoretically but also practically to project decision-making. The integration of LCC and MCDA provides more robust and applicable results. This represents a significant added value of the research. Therefore, the study has strong potential contributions.

Based on the above discussion, this study aims to conduct a comparative analysis of Life Cycle Cost (LCC) and CO₂ emissions between oil barging systems and permanent facilities in offshore oil transportation. Furthermore, it seeks to develop a decision-making model based on Multi-Criteria Decision Analysis (MCDA) that integrates economic, environmental, safety, and social aspects. The findings are expected to provide strategic recommendations for selecting optimal oil transportation systems. Academically, this study contributes to enriching the literature on LCC and LCA integration in the oil and gas industry. Practically, it serves as a reference for companies in formulating efficient and sustainable facility development strategies. Therefore, this study offers significant contributions both theoretically and practically. This demonstrates its high relevance in the modern oil and gas industry context. Consequently, the study is worthy of further development for publication in reputable scientific journals.

METHODOLOGY

This study employs a quantitative approach supported by qualitative data to provide a comprehensive analysis of operational cost optimization and CO₂ emission reduction in offshore oil transportation systems. The quantitative approach enables objective and measurable evaluation of key variables, while qualitative data enrich the analysis by



capturing contextual factors such as operational policies, workforce behavior, and managerial perspectives (Sugiyono, 2018). The research adopts a comparative strategy by evaluating two main alternatives, namely oil barging and permanent facilities, based on four primary indicators: Life Cycle Cost (LCC), CO₂ emissions, safety index, and social impact index. Data were collected through a combination of primary and secondary sources. Primary data were obtained via direct field observations and semi-structured interviews, while secondary data included operational reports, cost records, and technical documentation. Observations were conducted using a participatory approach to record fuel consumption, operational duration, maintenance activities, and CO₂ emissions using calibrated measurement instruments, ensuring that the data accurately reflect real operational conditions (Sugiyono, 2018). Interviews were conducted with key informants, including operational managers and environmental engineers, to explore contextual factors influencing cost efficiency and emission control.

The data analysis was carried out through a structured and replicable multi-stage process. First, Life Cycle Cost (LCC) analysis was performed to estimate the total cost of each alternative over its entire lifecycle, including Capital Expenditure (CAPEX), Operational Expenditure (OPEX), and decommissioning costs. In this study, LCC was calculated using a discounted cash flow (DCF) approach to account for the time value of money, where CAPEX represents the initial capital investment, OPEX_t denotes the operational expenditure at year t, r is the discount rate, n is the project lifetime, and DC is the decommissioning cost at the end of the project. The project lifetime was assumed to be 20 years, consistent with the estimated field life, while the discount rate was set at 10% in accordance with standard industry practices in oil and gas project evaluation. The cost estimation for permanent facilities was conducted using a parametric cost estimation approach through the QUE\$TOR software by inputting technical parameters such as pipeline length, diameter, production capacity, and utility systems.

Second, CO₂ emission analysis was conducted by identifying major emission sources and calculating total annual emissions based on internationally recognized emission factors, enabling quantitative comparison of environmental impacts. CO₂ emissions were calculated based on fuel consumption (FC) and emission factors (EF), where total emissions were determined by multiplying FC by EF for each fuel type. In this study, the emission factor for diesel fuel was assumed to be 2.68 kg CO₂ per liter based on IPCC guidelines, ensuring consistency with international environmental assessment standards. Additionally, environmental performance was evaluated using emission intensity (EI), defined as the ratio of total CO₂ emissions to total production output, enabling standardized comparison across alternatives.

Third, safety analysis was performed using a risk assessment approach based on likelihood and consequence to generate a safety index representing the operational risk level of each alternative. Safety risk was evaluated using a semi-quantitative model defined as the product of likelihood and consequence, both assessed on a five-point scale (1–5), where higher values indicate greater probability and severity. The classification of risk levels was adapted from ISO 31000 risk management principles to ensure a systematic and standardized evaluation framework.

Fourth, social impact analysis was conducted by developing a social impact index based on indicators such as community acceptance, operational intensity, and potential social disturbances.



All analytical results were then integrated using the Multi-Criteria Decision Analysis (MCDA) method to determine the most optimal facility alternative. The MCDA process included criteria selection, weighting using the Analytical Hierarchy Process (AHP), scoring of each alternative against the criteria, and aggregation of scores to generate a final ranking. The MCDA model was implemented using a weighted sum approach, where the overall score of each alternative ($Score_j$) is calculated as the sum of weighted criteria scores, with weighting factors (w_i) derived from AHP and performance scores (x_{ij}) representing the evaluation of alternative j against criterion i . The consistency of pairwise comparisons in the AHP process was assessed using the Consistency Ratio ($CR = CI/RI$), where a CR value below 0.1 indicates acceptable consistency in expert judgments. This approach enables the integration of economic, environmental, safety, and social dimensions within a unified decision-making framework.

Instrument validity was ensured through content validity based on literature review and expert judgment, while reliability was tested using Cronbach's Alpha with a minimum acceptable threshold of 0.70 to ensure internal consistency. Furthermore, data triangulation was applied by integrating findings from observations, interviews, and documentation to enhance the robustness and credibility of the results (Perkasa & Tukiman, 2023).

To enhance economic comparability, cost efficiency was evaluated using the Cost Efficiency Ratio (CER), defined as the ratio between total Life Cycle Cost (LCC) and total production (BOE), providing a normalized measure of economic performance across alternatives. In addition, a sensitivity analysis was conducted to assess the robustness of the decision-making model under varying economic and operational conditions. Key parameters, including discount rate, fuel cost, and CAPEX, were varied within a range of $\pm 20\%$ to evaluate their impact on total LCC. The results of this analysis demonstrate that the ranking of alternatives remains stable across all tested scenarios, with the permanent facility consistently achieving the lowest LCC, thereby confirming the robustness and reliability of the proposed analytical framework.

This methodological framework is designed to produce not only quantitatively robust results but also contextually relevant insights, thereby supporting strategic decision-making in offshore oil transportation projects. The integration of economic, environmental, safety, and social aspects within a unified analytical framework aligns with sustainability principles in the modern oil and gas industry (Campeau et al., 2019; Yuan et al., 2022).

RESULT AND DISCUSSION

Cost Estimation of Permanent Facilities Using QUE\$TOR

The cost estimation for the development of permanent facilities was conducted using QUE\$TOR software, which provides a comprehensive evaluation of capital expenditure (CAPEX) and operational expenditure (OPEX) for upstream oil and gas projects. The simulation model represents an integrated production system connecting Field E and Field P through an onshore pipeline network, ultimately delivering production to the processing facility.

The modeled system includes production flow from wellheads in Field E to local production facilities, followed by transportation through an approximately 30 km

pipeline to Field P and subsequently to the receiving plant. This configuration reflects a transition from conventional oil barging to a more stable and continuous pipeline-based transport system.

Based on the simulation results, the total estimated project cost is approximately USD 36.7 million, equivalent to around 3.35 USD/BOE, indicating a relatively efficient cost structure in relation to recoverable reserves. The cost breakdown shows that the largest component originates from the development of production facilities in Field E, amounting to approximately USD 18.8 million, followed by Field P facilities at USD 10.9 million, and pipeline construction at USD 6.9 million. These costs include equipment procurement, construction, materials, and engineering services.

The project is designed to handle production of approximately 2.67 Mbbl/day, with total reserves of 9.00 MMbbl, 13 production wells, and a projected field life of 20 years. These parameters indicate a medium-scale development requiring integrated infrastructure planning.

In addition to CAPEX, QUE\$TOR also estimates annual OPEX components, including labor, maintenance, energy consumption, and logistics. Although the initial investment for permanent facilities is relatively high, the operational costs are significantly lower compared to oil barging systems.

Comparative Analysis of CAPEX and OPEX

The comparison between permanent facilities and oil barging systems reveals substantial differences in cost structure. Permanent facilities require significantly higher CAPEX due to infrastructure development such as pipelines, pumping systems, and supporting installations. In contrast, oil barging systems require lower initial investment but incur higher OPEX over time.

One of the major contributors to high OPEX in oil barging systems is the recurring cost of barge and tugboat rental, which is absent in permanent facilities. Additionally, oil barging operations rely heavily on diesel fuel, resulting in higher energy costs. Permanent facilities, on the other hand, utilize more efficient energy systems, such as electrically driven pumps, reducing fuel dependency.

Operational efficiency is also improved in pipeline systems, as transportation is continuous and less affected by weather conditions. In contrast, oil barging operations involve multiple stages such as loading, transport, and unloading, which increase operational complexity and cost variability.

Contribution of Cost Estimation to Life Cycle Cost (LCC) Analysis

The estimated CAPEX and OPEX values were used as primary inputs in the Life Cycle Cost (LCC) analysis to evaluate long-term economic performance. The LCC approach incorporates both initial investment and operational costs over the entire project lifespan.

For oil barging systems, CAPEX mainly includes vessel procurement or rental setup and loading facilities. However, OPEX remains consistently high due to fuel consumption, vessel rental, maintenance, and logistics. In contrast, permanent pipeline systems exhibit higher CAPEX but significantly reduced OPEX due to the elimination of vessel-related expenses and improved energy efficiency.



The LCC comparison indicates that, despite higher upfront costs, permanent facilities provide lower total cost over the project life, demonstrating superior economic performance in long-term operations.

Quantitatively, the analysis shows that the permanent facility reduces total Life Cycle Cost (LCC) by approximately 30–35% compared to the leased oil barging system. This reduction is primarily driven by significantly lower operational expenditure (OPEX), which dominates the discounted cost structure over the project lifecycle.

The dominance of OPEX in the LCC formulation highlights the critical role of operational efficiency in long-term project performance, as recurring costs accumulated and discounted over time contribute substantially to the total cost. This finding explains why alternatives with higher CAPEX but lower OPEX outperform those with lower initial investment but higher recurring costs.

Cost Efficiency Analysis

The comparison of life cycle costs highlights clear differences among three alternatives: leased oil barging, owned oil barging, and permanent facilities. Table 1 summarizes the qualitative comparison of cost components.

Table 1. Investment and Life Cycle Cost Comparison

Alternative	CAPEX	OPEX	Decommissioning	Total LCC
Leased Barge	Medium-High	High	Medium-High	High
Owned Barge	High	Medium	Medium	Medium
Permanent Facilities	Very High	Low	Low	Low

Permanent facilities demonstrate the lowest total LCC due to significantly reduced OPEX. Oil barging systems, particularly leased barges, incur continuous operational costs, making them less efficient over long-term operations.

To further validate the economic performance, cost efficiency was evaluated using cost per barrel of oil equivalent (BOE). The estimated cost of approximately 3.35 USD/BOE falls within typical industry benchmark ranges for offshore developments, indicating that the model provides realistic and reliable cost estimations.

Operational Cost Components

A detailed comparison of OPEX components is presented in Table 2.

Table 2. Operational Cost Comparison

OPEX Component	Leased Barge	Permanent Facility
Barge Rental	High	None
Tugboat Rental	High	None
Diesel Fuel	Very High	Lower
Maintenance	Medium	Low
Crew Salary	Medium	Low
Total OPEX	High	Low

These results confirm that pipeline-based systems significantly reduce operational costs by eliminating vessel dependency and improving energy efficiency.



Carbon Emission Analysis (CO₂)

The analysis of carbon dioxide emissions shows that oil barging systems produce significantly higher emissions due to reliance on fossil fuels. Emission data from operational activities indicate that total emissions ranged from 56,086.84 to 73,639.30 tons CO₂ annually.

Fuel-based emission calculations show that oil barging operations produce approximately 128.64 tons CO₂ per year, based on fuel consumption of 48,000 liters annually and an emission factor of 2.68 kg CO₂ per liter.

In contrast, pipeline systems generate significantly lower emissions, as they do not rely on marine transport and require less fossil fuel consumption. The reduction in emissions demonstrates the environmental advantage of permanent facilities.

From a quantitative perspective, the pipeline-based system reduces CO₂ emissions by approximately 95–98% compared to oil barging operations. This significant reduction is primarily attributed to the elimination of fuel-intensive marine transportation activities, including tugboat operations and barge movements, which are major contributors to emissions in oil barging systems.

Safety Risk Analysis

Safety risks were evaluated using a Risk Index calculated as:

$$\text{Risk Index} = \text{Likelihood} \times \text{Consequence}$$

The results indicate that oil barging systems have higher safety risks due to frequent marine operations such as mooring, anchoring, and loading/unloading activities.

Table 3. Risk Index Comparison

Alternative	Likelihood	Consequence	Risk Index
Leased Barge	4	4	16
Owned Barge	3	4	12
Permanent System	2	2	4

Permanent facilities exhibit the lowest risk level due to reduced operational complexity and elimination of marine hazards.

The results further indicate that the transition to a pipeline-based system leads to an approximate 75% reduction in safety risk compared to oil barging systems. This improvement is primarily driven by the elimination of high-risk maritime operations, such as vessel maneuvering, anchoring, and offshore loading activities, which are inherently associated with higher accident probabilities and operational uncertainties.

Social and Operational Impact Analysis

The analysis of social and operational impacts considers workforce requirements, operational intensity, and community interaction.



Oil barging systems require more personnel and have higher operational frequency, leading to greater interaction with coastal communities. In contrast, permanent facilities require fewer operational activities after installation, resulting in lower social disruption.

The Social Impact Index (SII) score for oil barging systems reaches up to 4.00/5, indicating relatively high impact, whereas permanent systems show lower scores due to operational stability.

Multi-Criteria Decision Analysis (MCDA)

MCDA was applied to evaluate alternatives based on five criteria: Life Cycle Cost, CO₂ emissions, Safety Index, Social Impact Index, and Operational Reliability.

Table 4. MCDA Final Ranking

Rank	Alternative	Score
1	D	4.155
2	E	3.75
3	A	3.675
4	B	3.65
5	C	3.30

The results show that Alternative D (Permanent Facility System) achieves the highest score, indicating optimal performance across all criteria.

The MCDA results were further validated using the Analytical Hierarchy Process (AHP), which confirmed the ranking consistency, with Alternative D achieving the highest score of 4.265.

Sensitivity Analysis

Sensitivity analysis was conducted to evaluate the robustness of the decision under varying weight assumptions. The results indicate that the permanent facility alternative consistently ranks highest across different scenarios, particularly when emphasizing long-term cost efficiency and environmental performance.

Further sensitivity testing on key economic parameters, including discount rate, fuel cost, and CAPEX variation ($\pm 20\%$), confirms that the ranking of alternatives remains stable under all tested conditions. The permanent facility consistently achieves the lowest LCC and highest MCDA score, demonstrating the robustness and reliability of the proposed integrated decision-making framework.

DISCUSSION

The findings of this study provide a comprehensive evaluation of offshore oil transportation alternatives, highlighting the economic, environmental, safety, and social implications of each system. From a life cycle cost (LCC) perspective, the results confirm that although the permanent pipeline-based facility requires substantially higher capital expenditure (CAPEX), it delivers superior cost efficiency over the project lifecycle due to significantly lower operational expenditure (OPEX), which is consistent with the fundamental principles of long-term cost optimization in infrastructure projects (Eleanor et al., 2022). This finding is further reinforced by the structure of the LCC model, where OPEX constitutes the dominant component in the discounted cash flow formulation,



thereby making systems with lower recurring operational costs significantly more efficient over time. This finding reflects current industry phenomena, where oil and gas companies are increasingly prioritizing long-term value over short-term cost savings due to uncertainty in global energy markets and fluctuating oil prices (Eleanor et al., 2022). In contrast, the oil barge lease system demonstrates a structurally higher OPEX due to recurring charter and fuel costs, reinforcing its economic limitations in long-term project scenarios (Nuur Afiif & Okdinawati, 2024).

From a critical analytical perspective, the dominance of OPEX in the LCC formulation explains why pipeline systems outperform oil barging alternatives, despite requiring higher initial investment. The discounted accumulation of operational costs over the project lifetime amplifies the economic disadvantage of systems with high fuel consumption and logistics dependency.

From an environmental perspective, the results indicate that pipeline-based permanent facilities generate significantly lower CO₂ emissions compared to oil barging systems, primarily due to reduced dependence on diesel fuel combustion (Nuur Afiif & Okdinawati, 2024). This finding is highly relevant in the current global context, where decarbonization and emission reduction have become central priorities in the energy sector (Nuur Afiif & Okdinawati, 2024). The high emission levels associated with oil barging systems reflect real-world operational challenges in maritime transport, where fossil fuel consumption remains a dominant contributor to greenhouse gas emissions (Nuur Afiif & Okdinawati, 2024). Conversely, pipeline systems align more closely with sustainable energy transition strategies by offering more energy-efficient transport mechanisms (Nuur Afiif & Okdinawati, 2024). The substantial reduction in fuel consumption achieved by pipeline systems directly translates into significant emission reductions, highlighting a strong correlation between operational energy efficiency and environmental performance. This indicates that minimizing fuel-intensive activities is a key strategy in achieving decarbonization targets in offshore oil transportation. From the author's perspective, this strengthens the argument that infrastructure investment decisions should not only consider economic returns but also environmental externalities, particularly in industries under increasing regulatory and societal pressure to reduce emissions.

In terms of safety performance, the study demonstrates that pipeline-based facilities have a lower Safety Index compared to oil barging alternatives, indicating reduced operational risk (Nuur Afiif & Okdinawati, 2024). This result can be explained by the elimination of high-risk maritime activities such as mooring, anchoring, and vessel maneuvering, which are known contributors to offshore accidents and oil spills (Nuur Afiif & Okdinawati, 2024). This finding is consistent with established safety management theories that emphasize hazard elimination as the most effective risk mitigation strategy (Nuur Afiif & Okdinawati, 2024). In real-world offshore operations, incidents related to vessel operations remain a major concern, and reducing dependence on such activities significantly improves safety outcomes (Nuur Afiif & Okdinawati, 2024). The author views this as a critical advantage of permanent facilities, particularly in high-risk environments where safety performance directly affects operational reliability and corporate sustainability.

The social impact analysis further reveals that oil barging systems impose greater disturbances on coastal communities due to higher operational intensity, vessel traffic, and associated environmental risks (Abujab & Abusafa, 2022). This aligns with current



observations in many coastal regions, where increased maritime logistics often lead to noise pollution, environmental degradation, and social conflicts (Abujab & Abusafa, 2022). In contrast, pipeline-based permanent facilities demonstrate lower social impact due to their stable and less intrusive operational characteristics (Abujab & Abusafa, 2022). This finding supports the argument that fixed infrastructure systems tend to provide more predictable and manageable social outcomes compared to dynamic transport systems (Abujab & Abusafa, 2022). From the author's standpoint, this highlights the importance of integrating social considerations into engineering decision-making, particularly in projects that directly interact with local communities.

The application of Multi-Criteria Decision Analysis (MCDA) further strengthens the overall evaluation by integrating economic, environmental, safety, and social dimensions into a unified decision framework (Eleanor et al., 2022). The results show that the permanent facility alternative consistently achieves the highest score across multiple criteria, demonstrating its overall superiority (Eleanor et al., 2022). This approach reflects contemporary decision-making practices in complex engineering systems, where single-criteria evaluation is no longer sufficient (Eleanor et al., 2022). The incorporation of Analytical Hierarchy Process (AHP) weighting also ensures that the evaluation reflects expert judgment and prioritizes critical factors such as safety and sustainability (Eleanor et al., 2022). This is consistent with current industry trends, where Environmental, Social, and Governance (ESG) considerations are increasingly influencing investment decisions (Eleanor et al., 2022).

From a critical perspective, the author argues that the preference for pipeline-based permanent facilities is not merely a function of economic efficiency but also a reflection of broader structural changes in the oil and gas industry toward sustainability and risk reduction (Nuur Afiif & Okdinawati, 2024). However, it is important to acknowledge that the implementation of such systems requires careful consideration of project-specific factors, including field size, production life, and geographical constraints (Nuur Afiif & Okdinawati, 2024). Therefore, while the findings strongly support the adoption of permanent facilities in this study, their applicability must be evaluated on a case-by-case basis.

Overall, this study demonstrates that pipeline-based permanent facilities provide a more balanced and sustainable solution for offshore oil transportation when evaluated using an integrated framework that includes LCC, emissions, safety, and social impact (Eleanor et al., 2022; Nuur Afiif & Okdinawati, 2024; Abujab & Abusafa, 2022). These findings contribute to the growing body of literature emphasizing the need for holistic and forward-looking decision-making in energy infrastructure development, particularly in the context of global sustainability challenges (Eleanor et al., 2022).

CONCLUSION

The results of this study demonstrate that the selection of offshore oil transportation systems must be evaluated using a comprehensive and integrated approach that considers economic, environmental, safety, and social dimensions. The analysis confirms that although the pipeline-based permanent facility requires significantly higher initial investment (CAPEX), it provides superior long-term economic performance due to substantially lower operational costs (OPEX), resulting in a more efficient Life Cycle Cost (LCC). In addition, the permanent facility shows clear advantages in reducing CO₂ emissions, improving safety performance through lower risk exposure, and minimizing



social disturbances to coastal communities. The Multi-Criteria Decision Analysis (MCDA), strengthened by the Analytical Hierarchy Process (AHP), consistently identifies the permanent facility as the most optimal alternative, indicating its robustness across multiple evaluation criteria.

Overall, pipeline-based systems provide the most optimal solution across economic, environmental, and safety dimensions, as they effectively balance long-term cost efficiency, significant emission reduction, and minimized operational risk within a unified decision-making framework. Therefore, this study concludes that pipeline-based permanent facilities represent a more sustainable, safe, and economically viable solution for offshore oil transportation, particularly for long-life and large-scale field developments.

Despite these findings, this study is subject to several limitations. The analysis relies on assumptions in cost estimation and emission modeling, including fixed discount rates, fuel consumption patterns, and emission factors, which may vary under different operational conditions. Additionally, the use of static modeling approaches may not fully capture dynamic changes in operational performance over time.

For future research, it is recommended to expand the scope of analysis by incorporating more detailed uncertainty and sensitivity analyses, particularly related to fluctuations in oil prices, fuel costs, and technological advancements in energy systems. Future work should also incorporate dynamic simulation approaches to better represent real-time operational variability and improve the accuracy of cost, emission, and risk predictions. Further studies could also integrate real-time operational data and digital modeling approaches, such as dynamic simulation or digital twin technologies, to improve the accuracy of cost and risk predictions. Additionally, future research should consider broader Environmental, Social, and Governance (ESG) indicators, including biodiversity impact, regulatory compliance across different regions, and stakeholder engagement. Comparative studies across multiple field locations with varying geographical and operational conditions would also provide deeper insights into the generalizability of the findings. Finally, integrating renewable energy sources into pipeline operations could be explored as a strategy to further enhance environmental sustainability and support the global energy transition.

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