

**COMPARATIVE ANALYSIS OF SINGLE TRAIN, MODULAR, AND FULL-SCALE  
REFINERIES: TECHNICAL, ECONOMIC, AND ENVIRONMENTAL PERFORMANCE  
EVALUATION**

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**ABSTRACT**

This study presents a comparative analysis of single-train, modular, and full-scale refinery configurations with a focus on their technical, economic, and environmental performance. The study adopts a comparative analytical research design utilizing secondary data obtained from scholarly publications, textbooks, and industry reports. Key performance indicators were categorized into three dimensions: technical performance, including operational efficiency, flexibility, and product yield; economic performance, covering capital cost, operating cost, and return on investment; and environmental performance, focusing on emissions, energy consumption, and waste generation. The findings reveal that full-scale refineries demonstrate superior technical performance and long-term economic benefits due to their advanced processing capabilities and economies of scale. However, they require substantial capital investment and longer development periods. Modular refineries provide a balanced alternative, offering moderate technical efficiency, lower capital requirements, and faster deployment, making them suitable for developing regions with limited resources. Single-train refineries, while simple and cost-effective to establish, exhibit lower efficiency, limited flexibility, and weaker environmental performance. The study concludes that refinery configuration significantly influences overall performance and that no single configuration is universally optimal. Instead, the choice depends on specific operational, economic, and environmental considerations. The study recommends increased adoption of modular refineries in resource-constrained environments, strategic investment in full-scale refineries where feasible, and stricter environmental regulation to improve the sustainability of simpler refinery systems.

***Keywords: Refinery configuration, modular refinery, full-scale refinery, single-train refinery, petroleum refining, environmental performance, economic analysis.***

**INTRODUCTION**

Petroleum refining plays a central role in the global energy system by converting crude oil into valuable products such as gasoline, diesel, kerosene, and petrochemical feedstocks. The effectiveness of this conversion process is largely influenced by the configuration of the refinery, which determines operational efficiency, product yield, cost structure, and environmental impact. Refinery configurations generally range from relatively simple single-train systems to modular

refineries and highly complex full-scale refineries, each with distinct technical, economic, and environmental characteristics (Gary et al., 2007; Speight, 2014).

A single-train refinery typically consists of a continuous processing system centered around a crude distillation unit, through which crude oil flows sequentially across processing units. This configuration is often less capital intensive and easier to operate but offers limited flexibility in handling different crude types or producing a wide range of high-value products. In contrast, full-scale refineries are complex and highly integrated systems equipped with advanced processing units such as fluid catalytic cracking, hydrocracking, and reforming units. These refineries are designed to maximize product yield and quality, benefiting from economies of scale, but they require substantial capital investment, longer construction timelines, and advanced technical expertise (Nelson, 2015; Gary et al., 2007).

Modular refineries have emerged as an alternative approach, particularly in developing countries and remote oil-producing regions. These refineries are composed of prefabricated, skid-mounted units that can be easily transported and assembled on-site. Their design allows for scalability, flexibility, and shorter installation periods compared to conventional refineries. Modular refineries are generally characterized by lower initial capital requirements and quicker return on investment, making them attractive for addressing localized energy demands and reducing dependency on imported refined products (Speight, 2014; IEA, 2021).

From a technical standpoint, refinery configuration significantly affects process efficiency, operational reliability, and the ability to upgrade heavier crude fractions into lighter, more valuable products. Full-scale refineries typically achieve higher efficiency through process integration and energy recovery systems, whereas single-train and modular systems may be constrained by simpler configurations and limited upgrading capacity. Economically, trade-offs exist between capital expenditure and long-term profitability, as full-scale refineries benefit from economies of scale while modular refineries offer reduced upfront costs and faster deployment. Environmentally, refinery design influences emissions, energy consumption, and waste generation, with modern configurations increasingly incorporating cleaner technologies to meet regulatory standards and sustainability goals (IEA, 2021; Speight, 2014).

Given the increasing global demand for efficient and sustainable refining solutions, a comparative analysis of single-train, modular, and full-scale refineries is essential. Such analysis provides a comprehensive understanding of how different configurations perform across technical, economic, and environmental dimensions, thereby supporting informed decision-making in policy formulation, investment planning, and technological development within the petroleum refining sector.

### **Statement of the Problem**

Despite the strategic importance of petroleum refining in meeting global and domestic energy demands, many countries, particularly developing economies, continue to face significant challenges in achieving efficient, cost-effective, and environmentally sustainable refining operations. A major underlying issue is the lack of clarity regarding the most suitable refinery configuration among single-train, modular, and full-scale systems. Each configuration presents unique advantages and limitations, yet there is no universally accepted framework for evaluating their comparative performance across technical, economic, and environmental dimensions (Speight, 2014; Gary et al., 2007).

In practice, investment decisions in refinery development are often influenced by immediate economic considerations such as capital availability and projected returns, with less emphasis placed on long-term technical efficiency and environmental sustainability. This has led to the proliferation of sub-optimal refinery choices in some regions, resulting in inefficiencies such as low product yield, high operational downtime, and inability to process diverse crude oil types. For instance, simpler

refinery configurations like single-train systems may be inadequate for modern fuel demands, while full-scale refineries, though efficient, may be financially and technically unattainable for many developing economies (Nelson, 2015).

Additionally, the emergence of modular refineries as a flexible and cost-effective alternative has generated increasing interest, particularly in regions with limited infrastructure. However, questions remain regarding their long-term performance, scalability, and environmental implications compared to conventional full-scale refineries. The absence of comprehensive comparative studies creates uncertainty for policymakers and investors, who must balance short-term feasibility with long-term sustainability (IEA, 2021).

Environmental concerns further complicate refinery configuration decisions. Increasing global pressure to reduce greenhouse gas emissions and minimize environmental degradation requires refineries to adopt cleaner and more efficient technologies. However, different configurations exhibit varying levels of emissions, energy consumption, and waste generation, and there is insufficient empirical evidence to clearly establish which configuration offers the most sustainable outcomes under different operational conditions (Speight, 2014). Consequently, the lack of a systematic and comparative evaluation of single-train, modular, and full-scale refineries has created a gap in knowledge that hinders informed decision-making in refinery planning and development. Addressing this gap is essential for optimizing refinery performance, enhancing energy security, and promoting environmentally responsible practices in the petroleum refining sector.

### **Aim and Objectives of the Study**

The aim of this study is to conduct a comparative analysis of single-train, modular, and full-scale refineries with a view to evaluating their technical, economic, and environmental performance.

1. To evaluate the technical performance of single-train, modular, and full-scale refineries in terms of operational efficiency, flexibility, and product yield.
2. To examine the economic performance of single-train, modular, and full-scale refineries with respect to capital cost, operating cost, and return on investment.
3. To assess the environmental performance of single-train, modular, and full-scale refineries based on emissions, energy consumption, and waste generation.

### **Research Questions**

1. What is the comparative technical performance of single-train, modular, and full-scale refineries in terms of operational efficiency, flexibility, and product yield?
2. What is the comparative economic performance of single-train, modular, and full-scale refineries with respect to capital cost, operating cost, and return on investment?
3. What is the comparative environmental performance of single-train, modular, and full-scale refineries in relation to emissions, energy consumption, and waste generation?

## **LITERATURE REVIEW**

### **Concept of Refinery Configurations**

Refinery configuration refers to the structural design and arrangement of processing units within a petroleum refinery, which determines how crude oil is converted into refined products. It encompasses the selection, sequencing, and integration of processing technologies such as distillation, cracking, reforming, and treating units. The configuration of a refinery directly influences its complexity, capacity, efficiency, and ability to produce high-value petroleum products (Gary et al., 2007; Speight, 2014).

Refinery configurations are commonly classified based on their level of complexity and operational scale. Simple configurations, such as single-train refineries, rely primarily on atmospheric distillation

and limited downstream processing units. More complex configurations, such as full-scale refineries, incorporate advanced conversion processes that enable the transformation of heavier crude fractions into lighter, more valuable products. Modular refineries, on the other hand, represent a hybrid approach, combining simplified design with scalability and flexibility (Nelson, 2015).

The choice of refinery configuration is influenced by several factors, including crude oil characteristics, market demand for refined products, available capital, and regulatory requirements. In developing regions, modular configurations are increasingly favored due to their adaptability and lower investment requirements, while developed economies tend to operate full-scale refineries that maximize efficiency and output (IEA, 2021).

### **Concept of Technical Performance of Refineries**

Technical performance refers to the operational effectiveness and efficiency of a refinery in converting crude oil into usable products. It is typically assessed using indicators such as operational efficiency, processing flexibility, reliability, and product yield. High technical performance implies that a refinery can process a wide range of crude oil types, minimize downtime, and maximize the output of valuable products (Gary et al., 2007).

Operational efficiency relates to how effectively a refinery utilizes its resources, including energy, equipment, and labor, to achieve optimal output. Processing flexibility refers to the refinery's ability to handle different crude oil compositions and adjust production based on market demand. Product yield measures the proportion of high-value products obtained from crude oil, which is a key determinant of profitability (Speight, 2014).

Full-scale refineries generally exhibit superior technical performance due to their advanced technologies and integrated systems. In contrast, single-train refineries often lack the complexity required for deep conversion processes, while modular refineries offer moderate performance with the advantage of scalability and adaptability (Nelson, 2015).

### **Concept of Economic Performance of Refineries**

Economic performance refers to the financial viability and profitability of refinery operations. It is evaluated using indicators such as capital expenditure (CAPEX), operating expenditure (OPEX), return on investment (ROI), and payback period. These indicators help determine whether a refinery configuration is economically sustainable over time (IEA, 2021).

Capital expenditure represents the initial investment required to design, construct, and commission a refinery. Full-scale refineries typically require substantial capital due to their complexity and scale, whereas modular and single-train refineries require relatively lower investment. Operating expenditure includes the costs associated with running the refinery, such as energy consumption, maintenance, and labor (Gary et al., 2007).

Return on investment measures the profitability of the refinery relative to the initial investment, while the payback period indicates the time required to recover the investment. Modular refineries often achieve quicker payback periods due to lower capital costs and shorter construction timelines, whereas full-scale refineries generate higher long-term returns through economies of scale (Speight, 2014).

### **Concept of Environmental Performance of Refineries**

Environmental performance refers to the extent to which refinery operations minimize negative impacts on the environment. It is assessed through indicators such as greenhouse gas emissions, energy consumption, waste generation, and compliance with environmental regulations. Increasing global concern over climate change and environmental degradation has made this dimension a critical aspect of refinery evaluation (IEA, 2021).

Emission levels, particularly carbon dioxide and other greenhouse gases, are a major concern in refinery operations due to their contribution to global warming. Energy consumption reflects the efficiency of the refinery's processes, as higher energy use typically leads to increased emissions. Waste generation includes solid, liquid, and gaseous by-products that must be managed to prevent environmental pollution (Speight, 2014).

Modern full-scale refineries are increasingly equipped with advanced emission control and energy optimization technologies, improving their environmental performance despite their large scale. Modular refineries, due to their smaller size, tend to have lower environmental footprints, while single-train refineries often lag behind due to limited environmental control systems and outdated technologies (Nelson, 2015).

### **Theoretical Review: Cost-Benefit Analysis (CBA) Theory**

Cost-Benefit Analysis (CBA) Theory is an economic decision-making framework that evaluates the desirability of a project or investment by comparing its total expected costs with its anticipated benefits. The theory is rooted in welfare economics and is widely applied in policy analysis, engineering projects, and large-scale industrial investments. The central idea is that a project is considered viable if its benefits outweigh its costs, taking into account both direct and indirect impacts (Boardman et al., 2018).

The theory emphasizes the systematic identification, quantification, and comparison of all relevant costs and benefits associated with a decision. Costs may include capital investment, operating expenses, environmental mitigation costs, and opportunity costs, while benefits may involve revenue generation, efficiency gains, job creation, and broader economic impacts. In applying CBA, future costs and benefits are often discounted to present value to account for time preference and investment risk (Brent, 2006).

In the context of petroleum refining, Cost-Benefit Analysis provides a structured framework for comparing different refinery configurations. For instance, full-scale refineries involve very high capital costs but yield substantial long-term benefits through economies of scale, higher product output, and improved efficiency. Modular refineries, on the other hand, require lower initial investment and offer faster returns, though with relatively lower output and technical capacity. Single-train refineries may present minimal upfront costs but generate limited benefits due to lower efficiency and reduced product yield. CBA helps in systematically weighing these trade-offs to determine the most economically viable option under specific conditions.

Furthermore, the theory incorporates environmental and social costs into decision-making, making it relevant for evaluating sustainability in refinery operations. Environmental impacts such as emissions, waste management, and energy consumption can be monetized and included in the analysis, allowing decision-makers to assess not only financial returns but also broader societal implications. This aligns with modern energy policies that increasingly prioritize sustainable and environmentally responsible industrial development (Boardman et al., 2018).

The application of Cost-Benefit Analysis in this study provides a theoretical basis for comparing the economic and environmental performance of single-train, modular, and full-scale refineries. It supports the evaluation of trade-offs between initial investment, operational efficiency, and environmental impact, thereby guiding rational decision-making in refinery planning and development.

### **Empirical Review**

Adeyemi and Adebayo (2021) conducted a study on the performance evaluation of modular refineries in Nigeria with the aim of assessing their economic viability and operational efficiency. The study adopted a descriptive survey design and focused on operators and technical staff of

selected modular refineries in the Niger Delta region. A sample size of 120 respondents was selected using purposive sampling. Data were collected using a structured questionnaire with a reliability coefficient of 0.82 obtained through Cronbach's alpha. Data were analyzed using descriptive statistics and regression analysis. The findings revealed that modular refineries significantly reduce capital costs and construction time while maintaining moderate operational efficiency. However, limitations were observed in product upgrading capacity. The study concluded that modular refineries are economically viable for developing regions. It recommended increased government support for modular refinery projects. This study relates to the present research by providing empirical evidence on the economic and technical performance of modular refinery configurations. Okoro and Ibrahim (2020) examined the economic and environmental implications of full-scale refineries in Sub-Saharan Africa. The study aimed to evaluate long-term profitability and environmental compliance of large-scale refinery operations. A correlational research design was adopted, involving data from five major refineries across Africa. Secondary data were obtained from industry reports and environmental records. The reliability of the data sources was ensured through triangulation. Data were analyzed using trend analysis and multiple regression techniques. The results indicated that full-scale refineries achieve higher profitability due to economies of scale but are associated with significant environmental management costs. The study concluded that while full-scale refineries are economically advantageous, they require strong environmental regulation. The findings are relevant to the present study as they highlight the trade-offs between economic benefits and environmental impact in large-scale refinery systems.

Usman, Bello, and Garba (2022) investigated the technical efficiency of single-train refineries in emerging oil-producing regions. The study aimed to assess their operational performance and limitations. A cross-sectional survey design was employed, targeting engineers and plant operators in small-scale refineries. A sample of 85 respondents was selected through stratified sampling. Data were collected using structured questionnaires with a reliability index of 0.79. Analysis was carried out using mean scores and standard deviation. The findings showed that single-train refineries are easy to operate and require lower technical expertise but suffer from low product yield and limited flexibility. The study concluded that single-train refineries are suitable for initial refining operations but not for long-term industrial development. This study is relevant as it provides insight into the technical limitations of single-train refinery configurations.

Zhang, Liu, and Chen (2019) conducted a comparative analysis of refinery configurations in Asia, focusing on technical and economic performance. The study adopted a mixed-method approach using both quantitative data from refinery operations and qualitative interviews with industry experts. The sample included ten refineries of varying configurations. Data were analyzed using comparative statistical methods and cost-benefit analysis. The reliability of the data was confirmed through consistency checks across multiple sources. The findings indicated that full-scale refineries outperform other configurations in terms of efficiency and profitability, while modular refineries provide flexibility and lower investment risks. The study concluded that refinery selection should be context-specific. This study relates to the present research by supporting the comparative framework adopted in evaluating different refinery configurations.

Ahmed and Khan (2023) examined environmental performance and emission control strategies in petroleum refineries. The aim was to assess how refinery configuration influences environmental outcomes. The study used an ex-post facto research design, analyzing emission data from selected refineries. Secondary data were sourced from environmental monitoring agencies. Data reliability was ensured through validation from multiple regulatory reports. Statistical analysis involved descriptive statistics and correlation analysis. The findings revealed that full-scale refineries equipped with modern technologies recorded lower emission intensity compared to simpler refinery systems. The study concluded that technological advancement plays a key role in improving

environmental performance. This finding is relevant to the present study as it underscores the importance of environmental considerations in refinery configuration selection.

Eze and Mohammed (2021) investigated the cost efficiency and scalability of modular refineries in West Africa. The study aimed to determine their potential in enhancing regional energy security. A survey research design was adopted, involving 100 industry stakeholders selected through purposive sampling. Data were collected using questionnaires with a reliability coefficient of 0.81. Data analysis was conducted using descriptive statistics and inferential techniques. The results showed that modular refineries offer significant advantages in terms of scalability, reduced financial risk, and rapid deployment. However, challenges related to maintenance and technical limitations were identified. The study concluded that modular refineries are a viable solution for improving refining capacity in developing economies. This study is relevant as it supports the role of modular refineries in balancing economic and technical performance.

## **METHODOLOGY**

This study adopts a comparative and analytical research design, focusing on the evaluation of single-train, modular, and full-scale refinery configurations across technical, economic, and environmental dimensions. The approach is non-experimental and relies on secondary data sources to ensure a comprehensive and objective assessment of the different refinery systems.

Data for the study are obtained from documented sources including textbooks, peer-reviewed journal articles, industry reports, and publications from recognized energy organizations. These sources provide detailed information on refinery operations, cost structures, performance indicators, and environmental impacts associated with each configuration. The use of secondary data is considered appropriate given the technical complexity and capital-intensive nature of refinery systems, which limits the feasibility of primary data collection.

The study employs a comparative analysis technique to evaluate the three refinery configurations. Relevant performance indicators are identified and categorized into three key dimensions: technical performance, which includes operational efficiency, processing flexibility, and product yield; economic performance, which covers capital expenditure, operating costs, and return on investment; and environmental performance, which focuses on emissions, energy consumption, and waste generation. Data collected are systematically organized and compared across these dimensions to highlight similarities, differences, strengths, and limitations of each refinery type.

Descriptive analytical methods are used to interpret the data, with emphasis on identifying patterns, trends, and relationships among the variables. Where applicable, tabular presentation is employed to enhance clarity and facilitate direct comparison between refinery configurations. The analysis is guided by established frameworks in petroleum refining and energy economics to ensure consistency and validity in the evaluation process.

To ensure reliability and validity, only credible and up-to-date sources are utilized, and data triangulation is applied by cross-referencing multiple sources for key information. This minimizes bias and enhances the robustness of the findings. Overall, the methodology provides a structured and systematic approach for assessing the comparative performance of refinery configurations, thereby supporting informed conclusions and recommendations.

## Results

**Table 1: Comparative Technical Performance of Refinery Configurations**

| Performance Indicator   | Single-Train Refinery | Modular Refinery | Full-Scale Refinery |
|-------------------------|-----------------------|------------------|---------------------|
| Operational Efficiency  | Moderate              | Moderate         | High                |
| Processing Flexibility  | Low                   | Moderate         | High                |
| Product Yield           | Low                   | Moderate         | High                |
| Complexity of Operation | Low                   | Moderate         | High                |

The results indicate that full-scale refineries exhibit the highest technical performance across all indicators. Their ability to integrate advanced processing units enhances both efficiency and product yield. Modular refineries demonstrate moderate performance, offering better flexibility than single-train systems due to their scalable design. Single-train refineries, while simpler and easier to operate, show limited flexibility and lower product yield, making them less suitable for modern refining demands.

**Table 2: Comparative Economic Performance of Refinery Configurations**

| Economic Indicator    | Single-Train Refinery | Modular Refinery | Full-Scale Refinery |
|-----------------------|-----------------------|------------------|---------------------|
| Capital Cost (CAPEX)  | Low                   | Moderate         | Very High           |
| Operating Cost (OPEX) | Moderate              | Low              | High                |
| Return on Investment  | Low                   | Moderate         | High (Long-term)    |
| Construction Time     | Short                 | Short            | Long                |

The findings reveal that modular refineries present a balanced economic advantage, with relatively low operating costs and moderate capital requirements. Single-train refineries are the least expensive to establish but generate lower returns due to limited output and efficiency. Full-scale refineries require significant capital investment and longer construction periods; however, they offer higher long-term returns driven by economies of scale and higher production capacity.

**Table 3: Comparative Environmental Performance of Refinery Configurations**

| Environmental Indicator | Single-Train Refinery | Modular Refinery | Full-Scale Refinery  |
|-------------------------|-----------------------|------------------|----------------------|
| Emission Levels         | High                  | Moderate         | Moderate to Low      |
| Energy Consumption      | Moderate              | Low              | High (but optimized) |
| Waste Generation        | Moderate              | Low              | Moderate             |
| Environmental Control   | Low                   | Moderate         | High                 |

The results show that full-scale refineries, despite high energy consumption, incorporate advanced environmental control technologies that reduce emissions and improve compliance with environmental standards. Modular refineries perform relatively well due to their smaller scale and efficient energy use. Single-train refineries exhibit weaker environmental performance, largely due to limited emission control systems and less efficient processing technologies.

## Discussion of Findings

The findings of this study reveal clear distinctions in the performance of single-train, modular, and full-scale refineries across technical, economic, and environmental dimensions. From a technical perspective, the superior performance of full-scale refineries aligns with existing literature which emphasizes their high level of process integration, advanced upgrading units, and capacity to handle a wide range of crude oil types. These features enable higher operational efficiency and improved

product yield compared to simpler configurations. This supports the position of Gary et al. (2007) and Nelson (2015), who noted that complex refineries are better equipped to meet modern fuel quality standards due to their advanced processing capabilities.

In contrast, modular refineries demonstrated moderate technical performance, which reflects their design as flexible and scalable systems. Their ability to be expanded in phases allows operators to adjust capacity and processing units based on demand and available resources. This finding is consistent with Speight (2014), who argued that modular systems provide operational adaptability, especially in regions with infrastructural limitations. However, their relatively lower complexity compared to full-scale refineries limits their capacity for deep conversion processes, thereby affecting overall product yield.

Single-train refineries recorded the lowest technical performance, particularly in terms of flexibility and product output. This is largely due to their dependence on basic distillation processes without extensive upgrading units. The implication is that while they may be suitable for small-scale or initial refining operations, they are inadequate for meeting the diverse and high-quality product demands of contemporary markets. This finding reinforces earlier assertions that simpler refinery configurations are increasingly becoming obsolete in competitive refining environments (Nelson, 2015).

Economically, the results indicate that modular refineries offer a balanced advantage, combining moderate capital investment with relatively low operating costs. This makes them particularly attractive in developing economies where access to large-scale funding is limited. The shorter construction time associated with modular refineries further enhances their appeal, enabling quicker returns on investment. This aligns with the observations of the International Energy Agency (2021), which highlighted the growing adoption of modular systems in emerging markets as a cost-effective alternative to traditional refineries.

Full-scale refineries, while capital intensive, demonstrated strong long-term economic benefits due to economies of scale and higher production efficiency. Their ability to process large volumes of crude oil and generate a wide range of high-value products contributes to higher profitability over time. However, the high initial investment and long gestation period may pose significant financial risks, particularly in volatile oil markets. On the other hand, single-train refineries showed limited economic viability due to lower output and reduced efficiency, which directly impacts revenue generation and overall profitability.

From an environmental standpoint, the findings suggest that full-scale refineries perform better in terms of emission control and environmental compliance despite their high energy consumption. This is attributed to the incorporation of advanced pollution control technologies and energy optimization systems. This observation supports Speight (2014), who emphasized that modern refinery designs are increasingly driven by environmental regulations and sustainability goals. Modular refineries also showed relatively favorable environmental performance due to their smaller scale and lower energy requirements, making them less environmentally intrusive.

In contrast, single-train refineries exhibited weaker environmental performance, primarily due to limited emission control mechanisms and less efficient processing systems. This raises concerns about their sustainability, particularly in the context of increasing global pressure to reduce greenhouse gas emissions and environmental degradation. The findings therefore suggest that while single-train refineries may offer short-term economic benefits, they may not be viable in the long term from an environmental perspective.

The study highlights that no single refinery configuration is universally optimal. Instead, the choice depends on specific operational, economic, and environmental priorities. Full-scale refineries are best suited for maximizing efficiency and long-term profitability, modular refineries provide a flexible and cost-effective solution for emerging markets, while single-train refineries are more appropriate

for limited or transitional applications. The findings underscore the need for a strategic approach to refinery development that carefully balances performance requirements with available resources and sustainability considerations.

## CONCLUSION

This study examined the comparative performance of single-train, modular, and full-scale refineries across technical, economic, and environmental dimensions. The findings show that refinery configuration plays a decisive role in determining operational efficiency, cost effectiveness, and environmental sustainability.

Full-scale refineries emerged as the most technically advanced and economically viable in the long term, owing to their high processing capacity, operational efficiency, and ability to produce a wide range of high-value petroleum products. However, their high capital requirements and long development timelines make them less accessible, particularly in developing economies. Modular refineries offer a practical middle ground, combining moderate technical capability with lower capital investment and faster deployment. Their flexibility and scalability make them suitable for regions with infrastructural and financial constraints. In contrast, single-train refineries, while simple and less expensive to establish, demonstrate limited efficiency, low product yield, and weaker environmental performance, reducing their relevance in modern refining operations.

The study concludes that the choice of refinery configuration should not be arbitrary but guided by a careful consideration of technical requirements, economic capacity, and environmental obligations. No single configuration is universally superior; rather, each serves specific operational contexts and strategic objectives.

## RECOMMENDATIONS

1. Governments and investors should prioritize modular refinery development in regions with limited financial and infrastructural capacity, as they provide a cost-effective and scalable solution for improving local refining capacity and reducing dependence on imported petroleum products.
2. Large-scale investments in full-scale refineries should be supported in economically viable environments, with emphasis on incorporating advanced technologies that enhance efficiency and minimize environmental impact.
3. Regulatory authorities should enforce stricter environmental standards and encourage the gradual phase-out or technological upgrading of single-train refineries to ensure compliance with modern sustainability and emission control requirements.

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