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Enhancing Conversion Of Flared Natural Gas Into Liquefied Petroleum Gas For Industrial And Domestic Energy Use

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Abstract
Gas flaring remains a major environmental and economic challenge in Nigeria, resulting in the loss of valuable hydrocarbon resources and contributing to greenhouse gas emissions. This study evaluates the technical and economic feasibility of converting flared natural gas into Liquefied Petroleum Gas (LPG) for domestic and industrial energy utilization in the Niger Delta region of Nigeria. Process simulation was carried out using Aspen HYSYS Version 3.2 with the Peng–Robinson Equation of State to model gas dehydration, cryogenic Natural Gas Liquids (NGL) recovery, and hydrocarbon fractionation processes. A flare gas feed stream of 34.83 million standard cubic feet per day (MMScfd) was subjected to Triethylene Glycol (TEG) dehydration, cryogenic cooling, and separation through demethanizer, deethanizer, and depropanizer columns. Simulation results indicated that the proposed process could recover approximately 3.87 MMScfd of Liquefied Petroleum Gas, 4.01 MMScfd of ethane, and 25.10 MMScfd of methane. The recovered LPG contained propane and butane predominantly and corresponded to an annual production of approximately 74.96 million kilograms. Economic analysis showed an estimated annual revenue of ₦18.74 billion at an LPG selling price of ₦250 per kilogram. The results demonstrate that flare gas can be effectively converted into commercially valuable products while reducing environmental pollution associated with routine gas flaring. Although profitability depends on assumptions regarding market conditions and operating costs, the study confirms that LPG recovery from flared gas represents a technically feasible and economically attractive option for enhancing energy utilization and supporting sustainable development in Nigeria.

Keywords: *Aspen HYSYS; Economic Analysis; Gas Flaring; Liquefied Petroleum Gas; Natural Gas Liquids Recovery; Niger Delta.*

I. INTRODUCTION

Natural gas is an important energy resource that contributes significantly to power generation, industrial development, and domestic energy supply worldwide. Owing to its relatively lower carbon emissions compared to other fossil fuels, natural gas is increasingly recognized as a transitional fuel in the global shift toward cleaner energy systems (International Energy Agency, 2024; World Bank, 2024). However, large volumes of associated natural gas produced during crude oil extraction are still routinely flared in many oil-producing countries, particularly where gas processing and transportation infrastructure are inadequate (Federal Ministry of Petroleum Resources, 2022; Nigerian Midstream and Downstream Petroleum Regulatory Authority, 2024).

Gas flaring remains a major environmental and economic challenge in Nigeria, especially within the Niger Delta region. The practice results in the emission of greenhouse gases and atmospheric pollutants that contribute to climate change, environmental degradation, and public health concerns (Abu et al., 2023; Aigbe et al., 2023; United Nations Environment Programme, 2023). In addition to its environmental consequences, gas flaring leads to the destruction of valuable

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hydrocarbon resources such as methane, ethane, propane, and butane that could otherwise be processed into commercially useful products (Nwosu et al., 2021; Okoro et al., 2022).

One of the most promising approaches for flare gas utilization is the recovery of Liquefied Petroleum Gas. Liquefied Petroleum Gas consists mainly of propane and butane and is widely used for domestic cooking, industrial heating, transportation, and petrochemical applications (International Gas Union, 2023; World Liquefied Petroleum Gas Association, 2023). The increasing demand for cleaner household fuels in Nigeria further highlights the importance of developing efficient Liquefied Petroleum Gas recovery technologies from currently flared gas streams (Federal Ministry of Petroleum Resources, 2022). The recovery of Liquefied Petroleum Gas from natural gas commonly involves gas dehydration, cryogenic Natural Gas Liquids recovery, and hydrocarbon fractionation processes. Previous studies have demonstrated the effectiveness of cryogenic separation systems for recovering propane and butane from associated gas streams while maintaining high product purity and recovery efficiency (Aljubran et al., 2021; Khan et al., 2022; Hassan et al., 2023).

Furthermore, process simulation tools such as Aspen HYSYS have become valuable for evaluating gas processing systems, optimizing operating conditions, and predicting plant performance before implementation (Yusuf et al., 2022; Wang et al., 2024). Although several studies have investigated gas flare monetization and Natural Gas Liquids recovery, many focus primarily on either economic analysis or process simulation without integrating detailed process design, equipment sizing, product recovery assessment, and economic evaluation within a single framework (Obi & Okechukwu, 2022; Kumar et al., 2023; Zhang et al., 2023). Consequently, there remains a need for comprehensive studies that evaluate the technical and economic feasibility of Liquefied Petroleum Gas recovery from flare gas under Nigerian operating conditions.

The remainder of this paper is organized as follows. Section II presents the literature review on gas flaring, Liquefied Petroleum Gas recovery, and gas processing technologies. Section III describes the research methodology, simulation procedure, equipment design approach, and economic evaluation methods employed in the study. Section IV presents the simulation results, equipment design outputs, economic analysis, and discussion of findings. Finally, Section V provides the conclusions, limitations, recommendations, and directions for future research.

II. LITERATURE REVIEW

A. Gas Flaring and Environmental Impact

Gas flaring has remained a major environmental concern in oil-producing regions worldwide. It involves the controlled combustion of associated natural gas that cannot be economically processed, transported, or utilized at the point of production. Although flaring serves as a safety mechanism during process upsets and emergency operations, routine gas flaring represents a significant waste of energy resources and contributes substantially to atmospheric pollution. According to recent reports, billions of cubic meters of natural gas are flared annually across oil-producing countries, resulting in considerable greenhouse gas emissions and economic losses. Nigeria remains one of the largest gas-flaring countries globally despite possessing vast natural gas reserves. The Niger Delta region, which accounts for the majority of the country's crude oil production, has experienced decades of continuous gas flaring. Studies by Abu et al. (2023) and Aigbe et al. (2023) reported that gas flaring contributes significantly to carbon dioxide emissions, environmental degradation, and adverse health outcomes within host communities. Continuous exposure to flare emissions has been associated with respiratory disorders, reduced agricultural productivity, soil acidification, and ecosystem disturbances.

The environmental impact of gas flaring extends beyond local communities. Carbon dioxide and methane released during flaring contribute to global climate change by increasing atmospheric greenhouse gas concentrations. Incomplete combustion may also produce black carbon and other pollutants capable of affecting regional air quality. Consequently, governments and international organizations continue to advocate for the reduction of routine gas flaring through improved gas utilization technologies and stricter environmental regulations. The economic consequences of gas flaring are equally significant. Associated gas contains valuable hydrocarbon components such as methane, ethane, propane, and butane that can be processed into commercially useful products. The destruction of these hydrocarbons through flaring results in substantial revenue losses while simultaneously increasing environmental management costs. Therefore, the recovery and commercialization of flare gas have become strategic priorities within the petroleum industry.

B. Liquefied Petroleum Gas Recovery from Natural Gas

Liquefied Petroleum Gas is a mixture of low-molecular-weight hydrocarbons consisting primarily of propane and butane. It is widely recognized as one of the cleanest and most versatile hydrocarbon fuels available for domestic, commercial, and industrial applications. Due to its high calorific value, portability, ease of storage, and relatively low environmental impact, Liquefied Petroleum Gas has become increasingly important in global energy systems. The demand for Liquefied Petroleum Gas has increased significantly over the last decade, particularly in developing countries where governments are promoting cleaner cooking fuels to reduce dependence on biomass energy sources. In Nigeria, increasing urbanization, population growth, and government initiatives aimed at expanding access to clean energy have contributed to rising

Liquefied Petroleum Gas consumption. However, domestic production has often remained insufficient to satisfy market demand, leading to continued dependence on imports.

Natural gas processing provides one of the most effective means of producing Liquefied Petroleum Gas. During processing, heavier hydrocarbon components are separated from methane-rich gas streams through condensation and fractionation operations. Propane and butane recovered from Natural Gas Liquids are subsequently blended to produce commercial-grade Liquefied Petroleum Gas. The efficiency of Liquefied Petroleum Gas recovery depends on feed gas composition, operating conditions, process configuration, and equipment performance. Recent studies have demonstrated the feasibility of recovering Liquefied Petroleum Gas from flare gas streams. Okoro et al. (2022) reported that flare gas monetization through Liquefied Petroleum Gas production can generate substantial economic returns while simultaneously reducing greenhouse gas emissions.

Similarly, Eze and Nwankwo (2024) observed that integrated Natural Gas Liquids recovery systems significantly improve hydrocarbon utilization efficiency and reduce environmental impacts associated with routine flaring. Liquefied Petroleum Gas recovery offers several advantages compared with alternative flare gas utilization strategies. First, the technology is relatively mature and commercially proven. Second, Liquefied Petroleum Gas possesses an established market with growing demand. Third, the required processing infrastructure can be integrated into existing gas processing facilities. These advantages make Liquefied Petroleum Gas recovery an attractive option for flare gas commercialization.

C. Gas Dehydration and Hydrocarbon Fractionation Technologies

The successful recovery of Liquefied Petroleum Gas from natural gas requires efficient dehydration and fractionation processes. Raw natural gas streams typically contain varying amounts of water vapor that can create operational challenges during processing. Water may combine with hydrocarbons under low-temperature and high-pressure conditions to form gas hydrates, which can obstruct pipelines, valves, and processing equipment. Consequently, dehydration is a critical preliminary step in natural gas processing. Among the available dehydration methods, Triethylene Glycol dehydration remains the most widely employed technology within the natural gas industry. The process involves contacting wet natural gas with lean Triethylene Glycol within an absorber column. Water vapor is selectively absorbed by the glycol while dehydrated gas exits the top of the column. The water-rich glycol is subsequently regenerated and recycled for continued operation. According to Adeyemi et al. (2021), Triethylene Glycol dehydration can achieve water removal efficiencies exceeding 90%, making it suitable for cryogenic gas processing applications.

Following dehydration, hydrocarbon recovery is commonly achieved through cryogenic cooling and fractionation. Cryogenic processing involves reducing the gas temperature to extremely low values to condense heavier hydrocarbons while maintaining methane predominantly in the gaseous phase. The condensed liquids, collectively known as Natural Gas Liquids, are subsequently separated into individual components through distillation-based fractionation processes. The demethanizer is the first major fractionation column used in Natural Gas Liquids recovery systems. Its primary function is to separate methane from heavier hydrocarbon components.

Methane is recovered as the overhead product, while ethane, propane, butane, and heavier hydrocarbons are withdrawn from the bottom stream. High methane recovery is desirable because methane represents the largest fraction of natural gas and can be utilized for power generation or pipeline gas supply. The deethanizer receives the bottom product from the demethanizer and separates ethane from heavier hydrocarbons. Ethane is recovered as the overhead product and serves as an important feedstock for petrochemical manufacturing. The remaining propane- and butane-rich stream is subsequently processed in a depropanizer column.

The depropanizer separates propane and butane from heavier hydrocarbon fractions. The recovered propane and butane constitute the primary components of commercial Liquefied Petroleum Gas. Studies by Hassan et al. (2023) demonstrated that cryogenic fractionation systems can achieve high recovery efficiencies and product purities when properly designed and operated. The integration of Triethylene Glycol dehydration, cryogenic Natural Gas Liquids recovery, and hydrocarbon fractionation provides an effective means of converting flare gas into valuable products. However, the technical and economic performance of such systems depends on operating conditions, feed gas composition, equipment sizing, and process optimization strategies. Therefore, detailed process simulation and economic assessment remain essential for evaluating the feasibility of flare gas conversion projects.

D. Research Gap and Conceptual Framework

Previous studies have extensively examined gas flaring, Natural Gas Liquids recovery, and flare gas monetization strategies. However, most available studies focus primarily on either environmental assessments or economic evaluations without providing a comprehensive integration of process simulation, equipment design, hydrocarbon recovery analysis, and profitability assessment. Furthermore, limited research has specifically evaluated Liquefied Petroleum Gas recovery from representative Niger Delta flare gas streams using detailed Aspen HYSYS simulation and engineering design procedures. Additionally, many previous investigations provide insufficient information regarding simulation assumptions, equipment sizing methodology, process reproducibility, and product recovery efficiencies. This limitation makes it difficult to assess the industrial applicability of the proposed systems and compare performance across different studies.

To address these gaps, the present study integrates gas dehydration, cryogenic Natural Gas Liquids recovery, hydrocarbon fractionation, equipment design, and economic evaluation within a unified simulation framework. The study provides a detailed assessment of Liquefied Petroleum Gas production from flare gas while considering technical feasibility, product quality, hydrocarbon recovery efficiency, equipment requirements, and project profitability. This integrated approach contributes to existing knowledge by providing a more comprehensive evaluation of flare gas utilization opportunities under Nigerian operating conditions.

III. RESEARCH METHODS

A. Research Design

This study employed a simulation-based engineering research design to evaluate the technical and economic feasibility of converting flared natural gas into Liquefied Petroleum Gas (LPG) for domestic and industrial energy applications. The research framework integrated process simulation, equipment sizing, hydrocarbon recovery assessment, and preliminary economic evaluation. Aspen HYSYS Version 3.2 was used to model the principal processing stages, including gas dehydration, cryogenic Natural Gas Liquids (NGL) recovery, and hydrocarbon fractionation. The outputs generated from the simulation were subsequently used as the basis for equipment design calculations, product recovery evaluation, and economic analysis. The integrated approach was adopted because technical process performance alone is insufficient to determine the practical feasibility of a flare gas recovery project. Therefore, the study simultaneously considered process operability, separation performance, equipment requirements, recoverable product quantities, and potential economic value. This framework enabled the proposed LPG recovery system to be assessed from both engineering and commercial perspectives.

B. Data Sources and Input Parameters

The data used in this study were obtained from operating flow stations located in the Niger Delta region of Nigeria. Field operational records and process reports provided information on flare gas composition, feed flow rate, operating pressure, operating temperature, production capacity, and relevant process conditions. The selected feed represents associated natural gas that is routinely flared because of limited gas-processing infrastructure. The gas composition obtained from the field records served as the principal input for the development of the Aspen HYSYS model. In addition to process data, product specifications, equipment operating requirements, and economic assumptions were incorporated into the analysis. The principal data categories used in the study are summarized in Table 1.

Table 1. Principal Data Inputs Used in the Simulation and Economic Evaluation

Data Category	**Application in the Study**
Gas composition	Definition of hydrocarbon and non-hydrocarbon components in the feed stream
Feed gas flow rate	Determination of process throughput and equipment capacity
Operating pressure	Specification of processing and separation conditions
Operating temperature	Definition of dehydration, cryogenic cooling, and fractionation conditions
Product specifications	Evaluation of recovered methane, ethane, and LPG streams
Equipment operating parameters	Equipment sizing and process-performance assessment
Economic parameters	Estimation of production, revenue, capital requirements, and profitability

As indicated in Table 1, the input data supported both the technical simulation and the subsequent economic assessment. A design feed gas flow rate of 34.83 million standard cubic feet per day (MMScfd) was adopted as the reference throughput and was consistently applied throughout the process simulation and economic calculations.

C. *Process Simulation Procedure*

The process simulation was developed in Aspen HYSYS Version 3.2. The Peng–Robinson Equation of State was selected as the thermodynamic property package because of its suitability for predicting phase behavior and vapor–liquid equilibrium in hydrocarbon mixtures, particularly under the low-temperature conditions associated with cryogenic NGL recovery. The simulation began with characterization of the flare gas feed based on the field-derived composition. All hydrocarbon and non-hydrocarbon components present in the feed were defined in the simulation environment. The gas was subsequently processed through a Triethylene Glycol (TEG) dehydration unit to remove water vapor before cryogenic treatment. This step was required to minimize the possibility of hydrate formation during low-temperature processing.

Following dehydration, the gas was cooled to approximately −95 °C using a refrigeration system. At this temperature, the heavier hydrocarbon fractions condensed while methane remained predominantly in the gaseous phase. The cooled stream was then introduced into the demethanizer, where methane was separated from the heavier hydrocarbons. The bottom product from the demethanizer was directed to the deethanizer for ethane recovery, while the remaining propane- and butane-rich stream was subsequently processed in the depropanizer to recover LPG.

The final simulation outputs were used to determine the quantities and compositions of the methane, ethane, and LPG product streams.

These outputs also provided the basis for equipment sizing and economic evaluation. The overall sequence therefore followed a continuous pathway from feed characterization → dehydration → cryogenic cooling → demethanization → deethanization → depropanization → product recovery → economic assessment. This simulation sequence is consistent with the processing stages specified in the original research design.

D. Equipment Design Method

The principal process equipment required for the proposed LPG recovery facility was sized using simulation outputs and standard petroleum engineering design procedures. Equipment dimensions and capacities were determined from the corresponding flow rates, operating pressures, residence-time requirements, and separation duties obtained from the Aspen HYSYS model. Rather than treating each equipment item independently, the design followed the functional sequence of the overall process. The main equipment and their respective purposes are summarized in Table 2.

Table 2. Major Process Equipment and Design Functions

Equipment	**Main Design Function**
Inlet Gas Scrubber	Removal of entrained liquids and solid particles before dehydration
TEG Contactor	Removal of water vapor to achieve suitable conditions for cryogenic processing
Demethanizer Column	Separation of methane from heavier hydrocarbon components
Deethanizer Column	Recovery of ethane from the NGL-rich stream
Depropanizer Column	Recovery of propane- and butane-rich LPG
Heat Exchangers	Heat transfer and temperature adjustment within the process
Pumps	Liquid transport and pressure requirements
Compressors	Gas compression and pressure control

As shown in Table 2, each unit performs a specific function within the integrated recovery process. The inlet scrubber was sized to protect downstream equipment by removing entrained liquids and solids, while the TEG contactor was designed to provide adequate gas–glycol contact for water removal. The fractionation columns were designed according to the required separation performance and product-purity specifications. Heat exchangers, pumps, and compressors were selected according to the thermal and hydraulic requirements obtained from the simulation.

E. Economic Evaluation Method

A preliminary engineering economic analysis was conducted to evaluate the commercial potential of the proposed flare gas conversion system. The assessment considered annual LPG production, annual revenue generation, capital investment requirements, project profitability, and the potential economic value associated with gas that would otherwise be lost through routine flaring.

Annual revenue was estimated from the simulated LPG production rate and the assumed market selling price. The principal economic assumptions adopted for the analysis are presented in Table 3.

Table 3. Economic Assumptions Used in the Project Evaluation

Parameter	Assumption
Plant operating period	350 days/year
Project life	20 years
LPG selling price	₦250/kg
Exchange rate	₦150/USD
Corporate income tax	30%
Depreciation method	Straight-line

The assumptions in Table 3 provided a consistent basis for the preliminary economic calculations. They were intended to represent the conditions adopted for this study rather than fixed future market values. Consequently, the resulting economic indicators were interpreted as preliminary estimates because actual commercial performance may vary with changes in LPG prices, exchange rates, operating costs, taxation, and other market conditions. The economic assumptions reported here are those specified in the manuscript.

F. Data Analysis Technique

The Aspen HYSYS simulation outputs were evaluated using descriptive engineering performance indicators. The technical assessment focused on the effectiveness of water removal, hydrocarbon separation, product recovery, product composition and purity, and the operating performance of the principal process equipment. Methane, ethane, and LPG recovery were evaluated separately to determine how effectively each product was separated from the original flare gas stream.

The economic analysis used the simulated LPG production rate to estimate annual production and revenue, while capital requirements and profitability indicators were used to assess preliminary commercial feasibility. Thus, the analytical framework linked process performance directly to economic performance: simulation results determined product quantities, and those product quantities subsequently provided the basis for estimating economic value. The resulting technical and economic outputs were presented in tabular form and interpreted according to their engineering significance and potential industrial applicability.

G. Mathematical Models

The annual Liquefied Petroleum Gas production was calculated using Equation (1).

$$Q_{annual} = Q_{hourly} \text{ x } 24 \text{ x } \mathrm{D} \qquad (1)$$

Where, Q_{annual} as annual liquefied petroleum gas production (kg/year), Q_{hourly} as hourly LPG production rate (kg/hour), and D denotes the number of operating days per year. Annual revenue generated from Liquefied Petroleum Gas sales was calculated using Equation (2).

$$R = Q_{annual} \text{ x } P_{LPG} \qquad (2)$$

Where, R as an annual revenue (₦/year), Q_{annual} denotes annual LPG production (kg/year), and P_{LPG} is the LPG selling price (₦/kg). Hydrocarbon recovery efficiency was determined using Equation (3).

$$\eta = \frac{Q_{product}}{Q_{feed}} \text{ x } 100 \qquad (3)$$

Where, η denotes recovery efficiency (%), $Q_{product}$ is the quantity of recovered product, and Q_{feed} for quantity of product in the feed stream. The simple payback period was estimated using Equation (4).

$$PBP = \frac{CI}{NCF} \qquad (4)$$

Where, PBP = Payback period (years), CI = Capital investment (₦), and NCF = Annual net cash flow (₦/year). Last, the Peng–Robinson Equation of State employed in Aspen HYSYS is expressed as:

$$P = \frac{RT}{V-b} - \frac{a}{V(V+b)+b(V-b)} \qquad (5)$$

where P is pressure, R is the universal gas constant, T is absolute temperature, V is molar volume, a represents the attractive-force parameter, and b represents the co-volume parameter. The Peng–Robinson Equation of State was employed because it provides an appropriate thermodynamic representation of hydrocarbon phase behavior and vapor–liquid equilibrium under the conditions encountered in natural gas processing. Its application therefore supported the simulation of cryogenic separation and subsequent hydrocarbon fractionation stages.

IV. RESULTS

The Aspen HYSYS simulation produced a complete mass-separation profile for the proposed flare gas recovery system, covering feed characterization, gas dehydration, methane and ethane separation, LPG recovery, equipment sizing, and preliminary economic performance. The results are presented sequentially according to the major processing stages.

A. Feed Gas Characterization

The composition of the flare gas feed provides the basis for evaluating its potential for Natural Gas Liquids (NGL) and Liquefied Petroleum Gas (LPG) recovery. Gas samples from two operating flow stations in the Niger Delta were characterized according to their hydrocarbon and non-hydrocarbon components. The compositions of Flow Stations 1 and 2 are presented in Tables 4 and 5, respectively.

Table 4. Composition of Flow Station 1 Gas

Component	Mole Fraction
Nitrogen	0.0011
Carbon Dioxide	0.0106
Methane	0.6897
Ethane	0.1386
Propane	0.0971
Iso-butane	0.0304
Normal Butane	0.0196
Iso-pentane	0.0030
Water	0.0099

As shown in Table 4, methane was the dominant component of the Flow Station 1 gas stream, with a mole fraction of 0.6897 or approximately 68.97%. The stream also contained appreciable quantities of ethane, propane, iso-butane, and normal butane, indicating the presence of recoverable heavier hydrocarbons suitable for downstream NGL and LPG processing.

Table 5. Composition of Flow Station 2 Gas

Component	Mole Fraction
Nitrogen	0.0010
Carbon Dioxide	0.0009
Methane	0.7221
Ethane	0.1175
Propane	0.0799
Iso-butane	0.0204
Normal Butane	0.0197
Iso-pentane	0.0147
Normal Pentane	0.0102
Normal Hexane	0.0037
Water	0.0099

A similar pattern was observed for Flow Station 2, where methane represented the largest fraction at 0.7221. The gas also contained ethane, propane, butanes, pentanes, and hexane. The presence of these heavier hydrocarbons in both streams confirmed that the flare gas contained sufficient recoverable components to proceed with detailed dehydration, cryogenic separation, and fractionation analysis.

B. Gas Dehydration Results

Before cryogenic processing, the combined gas stream was treated using a Triethylene Glycol (TEG) dehydration system. The operating conditions of the gas–TEG contactor are presented in Table 6. Gas dehydration was carried out using a Triethylene Glycol dehydration system to remove water vapor before cryogenic processing. Dehydration is essential because the presence of water can lead to hydrate formation under low-temperature operating conditions.

Table 6. Operating Conditions of Gas–Triethylene Glycol Contactor

Parameter	Gas Feed	Dry Gas	Lean TEG	Rich TEG
Temperature (°C)	25.00	27.36	40.00	26.18
Pressure (bar)	13.01	12.80	13.30	13.01
Flow Rate (MMScfd)	34.57	34.49	0.10	0.18

As indicated in Table 6, the gas flow rate decreased only slightly from 34.57 MMScfd at the inlet to 34.49 MMScfd after dehydration. This small difference indicates that the dehydration stage removed water with minimal loss of the hydrocarbon gas stream. The change in gas composition before and after TEG treatment is presented in Table 7.

Table 7. Gas Composition Before and After Dehydration

Component	Wet Gas	Dry Gas
Nitrogen	0.0010	0.0010
Carbon Dioxide	0.0058	0.0058
Methane	0.7114	0.7131
Ethane	0.1291	0.1294
Propane	0.0886	0.0888
Iso-butane	0.0256	0.0257
Normal Butane	0.0198	0.0198
Iso-pentane	0.0089	0.0089
Normal Pentane	0.0051	0.0051
Normal Hexane	0.0019	0.0019
Water	0.0025	0.0002

The water mole fraction decreased from 0.0025 in the wet gas to 0.0002 in the dry gas, corresponding to a water-removal efficiency greater than 90%. At the same time, the concentrations of the principal hydrocarbon components remained essentially unchanged. The dehydrated stream therefore provided the feed condition required for the subsequent cryogenic separation process.

C. Demethanizer Performance Results

Following dehydration and cryogenic cooling to approximately −95 °C, the gas stream was introduced into the demethanizer column. The operating conditions and major component distributions are summarized in Table 8 and Table 9.

Table 8. Demethanizer Separation Results

Parameter	Feed	Overhead Product	Bottom Product
Temperature (°C)	-95.00	-92.45	32.73
Pressure (bar)	22.75	22.75	23.10
Flow Rate (MMScfd)	34.48	25.10	9.39
Normal Butane	0.0198	0.0000	0.0728

As shown in Table 8, the demethanizer produced an overhead gas flow of approximately 25.10 MMScfd, containing methane at a mole fraction of approximately 0.9800. The bottom stream had a flow rate of 9.39 MMScfd and retained most of the ethane, propane, and butane fractions required for subsequent hydrocarbon fractionation.

Table 9. Major Component Distribution

Component	Feed	Overhead	Bottom
Methane	0.7132	0.9800	0.0000
Ethane	0.1294	0.0121	0.4428
Propane	0.0889	0.0010	0.3236
Iso-butane	0.0257	0.0001	0.0941

D. Deethanizer Performance Results

The demethanizer bottom stream was subsequently processed in the deethanizer column to separate ethane from the heavier hydrocarbon fractions. The resulting operating conditions and component distributions are presented in Table 10 and 11.

Table 10. Deethanizer Separation Results

Parameter	Feed	Ethane Product	Bottom Product
Temperature (°C)	33.42	-2.97	92.65
Pressure (bar)	27.90	22.75	27.92
Flow Rate (MMScfd)	9.39	4.01	5.27

The deethanizer generated approximately 4.01 MMScfd of ethane product with a mole fraction of 0.9713, equivalent to approximately 97.13% purity. The remaining bottom product had a flow rate of 5.27 MMScfd and was predominantly composed of propane and butane, providing the feed for the final LPG recovery stage.

Table 11. Major Component Distribution

Component	Feed	Ethane Product	Bottom Product
Ethane	0.4428	0.9713	0.0301
Propane	0.3236	0.0117	0.5674
Iso-butane	0.0941	0.0000	0.1675
Normal Butane	0.0728	0.0000	0.1296

E. LPG Recovery through Depropanization

The propane- and butane-rich stream leaving the deethanizer was processed in the depropanizer, which represented the final hydrocarbon fractionation stage. The process conditions and resulting LPG composition are summarized in Table 12 and Table 13.

Table 12. Depropanizer Separation Results

Parameter	Feed	LPG Product	Bottom Product
Temperature (°C)	69.57	49.02	112.93
Pressure (bar)	16.90	15.85	16.55
Flow Rate (MMScfd)	5.27	3.87	1.40

The depropanizer recovered approximately 3.87 MMScfd of LPG. Propane was the dominant component of the recovered stream at 76.59%, followed by iso-butane at 12.23%, normal butane at 6.63%, and ethane at 4.10%. The simulation therefore produced an LPG stream composed predominantly of propane and butane, which are the principal hydrocarbon components of commercial LPG. Taken together, the fractionation sequence produced three principal

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recoverable streams: approximately 25.10 MMScfd of methane, 4.01 MMScfd of ethane, and 3.87 MMScfd of LPG. These results establish the material recovery profile generated by the proposed process configuration.

Table 13. Liquefied Petroleum Gas Product Composition

Component	Composition (%)
Ethane	4.10
Propane	76.59
Iso-butane	12.23
Normal Butane	6.63

F. Equipment Design Results

Equipment sizing was performed using the operating conditions and flow rates obtained from the Aspen HYSYS simulation. The principal design specifications for the inlet gas scrubber and TEG contactor are presented in Tables 14 and 15.

Table 14. Scrubber Design Specifications

Parameter	Value
Vessel Size	60 inches × 15 feet
Working Pressure	230 psig
Operating Pressure	174 psig
Gas Capacity	38.1 MMScfd
Connection Size	6 inches
Shipping Weight	26,500 pounds

The inlet scrubber has a rated gas capacity of 38.1 MMScfd, which exceeds the design feed rate used in the simulation. The selected vessel dimensions and operating pressure therefore provide the required capacity for handling the proposed feed stream before dehydration.

Table 15. Glycol Contactor Design Specifications

Parameter	Value
Working Pressure	500 psig
Diameter	48 inches
Gas Capacity	35.1 MMScfd
Gas Connection	6 inches
Glycol Connection	2 inches
Shipping Weight	10,000 pounds

As shown in Table 15, the glycol contactor has a gas-handling capacity of 35.1 MMScfd, which is slightly above the design gas throughput. The specified dimensions and connections provide the required contact capacity for the TEG dehydration stage.

G. Economic Analysis Results

The economic evaluation was based on the LPG production rate obtained from the Aspen HYSYS simulation and the economic assumptions defined in the methodology. The simulated LPG production rate was approximately 8,924 kg/h. Assuming plant operation for 350 days per year and 24 operating hours per day, the annual LPG production was calculated as:

$$Q_{annual} = 8{,}924 x 24 x 350$$

$$Q_{annual} = 74{,}961{,}600\ kg/year$$

Accordingly, the proposed process could produce approximately 74.96 million kg of LPG per year. Using the assumed LPG selling price of ₦250/kg, the corresponding annual revenue was calculated as:

$$R = 74{,}961{,}600 \times 250$$

$$R = ₦18{,}740{,}400{,}000\ per\ year$$

Therefore, the estimated annual revenue from LPG sales was approximately ₦18.74 billion per year. In comparison, the estimated total capital investment required for the proposed facility was approximately ₦40 billion. The principal technical and economic outputs obtained from the simulation and subsequent calculations are summarized in Table 16.

Table 16. Summary of Major Process and Economic Results

Indicator	**Result**
Design feed gas flow rate	34.83 MMScfd
Methane recovered	25.10 MMScfd
Methane purity	≈ 98%
Ethane recovered	4.01 MMScfd
Ethane purity	≈ 97.13%
LPG recovered	3.87 MMScfd
LPG production rate	8,924 kg/h
Annual LPG production	74,961,600 kg/year
Assumed LPG selling price	₦250/kg
Estimated annual LPG revenue	≈ ₦18.74 billion/year
Estimated capital investment	≈ ₦40 billion

As shown in Table 16, the simulated process produced three commercially relevant hydrocarbon streams, including methane, ethane, and LPG. The LPG stream alone corresponded to an estimated annual production of approximately 74.96 million kg and projected annual sales revenue of approximately ₦18.74 billion under the assumed market price. These results provide the quantitative basis for the subsequent assessment of the technical feasibility, economic viability, and potential contribution of flare gas recovery to improved resource utilization.

V. DISCUSSION

The simulation results indicate that the proposed flare-gas conversion system can support an integrated recovery pathway in which water removal, cryogenic separation, and hydrocarbon fractionation operate sequentially to produce usable methane, ethane, and LPG streams. The importance of the configuration lies not only in the performance of each individual processing unit but also in the continuity of the overall separation sequence. Adequate gas conditioning preserves recoverable hydrocarbons, while subsequent fractionation progressively separates the lighter and heavier components into commercially useful streams. This integrated behavior provides the principal technical basis for evaluating flare gas as a recoverable energy resource rather than as a waste stream.

A. Technical Performance and Process Feasibility

Effective dehydration is fundamental to the proposed configuration because cryogenic processing requires sufficiently dry feed gas to minimize hydrate formation, corrosion, blockage, and operational instability. The performance obtained from the TEG system falls within the range reported for properly designed natural-gas dehydration systems by Adeyemi et al. (2021). More importantly, water removal occurred without substantial depletion of the hydrocarbon fraction. This is technically desirable because dehydration should condition the gas for low-temperature processing while preserving the components that provide the economic value of the downstream recovery process.

The performance of the fractionation train further supports the suitability of the selected process configuration. The demethanizer effectively separated a high-purity methane stream while retaining the heavier hydrocarbons for downstream processing. Its performance is comparable with the methane purity range reported by Hassan et al. (2023) for cryogenic NGL recovery systems. This agreement provides additional support for the selected thermodynamic and operating conditions. The recovered methane also broadens the utilization potential of the process because it can serve as an energy stream for applications such as power generation, industrial fuel supply, pipeline gas, or other natural-gas applications rather than being destroyed through flaring.

The subsequent recovery of ethane demonstrates that the proposed configuration is not limited to LPG production alone. Separating ethane before LPG recovery improves the definition of the downstream propane- and butane-rich stream while creating an additional potentially valuable petrochemical feedstock. The combined recovery of methane, ethane, and LPG therefore represents a more comprehensive utilization strategy than a single-product flare-gas conversion scheme. From an engineering perspective, this improves resource efficiency because several valuable fractions of the original associated gas are retained for potential commercial use.

The final LPG stream is particularly relevant because propane and butane constitute its dominant components. The resulting composition indicates that cryogenic NGL recovery followed by staged fractionation can transform the heavier fraction of the flare gas into a useful fuel stream for domestic and industrial applications. In the Nigerian context, this has practical relevance because LPG can contribute to cleaner household and industrial energy supply while simultaneously reducing the amount of associated gas sent to flare.

Technical feasibility is also supported by the compatibility between the simulated process throughput and the equipment design specifications. The scrubber and glycol contactor capacities are sufficient for the selected feed conditions, while the successful convergence of the Aspen HYSYS model across dehydration, cryogenic cooling, demethanization, deethanization, and depropanization indicates that the configuration is thermodynamically workable under the modeled operating conditions. These results provide a reasonable basis for advancing the concept toward more detailed engineering evaluation. Nevertheless, simulation convergence and equipment sizing should not be interpreted as equivalent to demonstrated plant-scale operability; field validation remains necessary before industrial implementation.

B. Resource Utilization and Environmental Implications

A major implication of the proposed configuration is the conversion of hydrocarbons that would otherwise be combusted through routine flaring into potentially useful energy and feedstock products. This represents an improvement in resource utilization because the associated gas is treated as a recoverable asset rather than an unavoidable waste stream. Such an approach is consistent with the broader transition from flare disposal toward gas monetization strategies. The environmental benefit follows from the same principle. Routine flaring is associated with greenhouse-gas emissions and other atmospheric pollutants, while the destruction of recoverable hydrocarbons also represents inefficient use of a finite energy resource. Redirecting part of the flare stream to useful products can therefore reduce the quantity of gas requiring routine combustion and simultaneously increase the productive use of associated gas. This interpretation is consistent with Abu et al. (2023), who reported that flare-gas utilization can combine environmental mitigation with economic value creation.

However, the present study does not quantify the actual reduction in carbon dioxide equivalent emissions, methane emissions, black carbon, or other pollutants. Consequently, the environmental advantage should be interpreted as a technically plausible implication of reducing routine flaring rather than as a measured environmental performance outcome. A full environmental assessment would require a detailed emissions inventory, energy-consumption analysis for the recovery facility, and comparison of the proposed system with the existing flaring baseline.

C. Economic Implications

The economic analysis indicates that the recovered LPG has substantial revenue-generating potential, supporting the broader argument that flare gas can represent an economically useful feedstock. This finding is consistent with previous studies that have identified associated-gas recovery and NGL production as potential pathways for monetizing resources that would otherwise be wasted (Nwosu et al., 2021; Kumar et al., 2023; Zhang et al., 2023). The additional methane and ethane streams may provide further commercial value and improve overall project economics if suitable markets or internal utilization pathways are available. Nevertheless, revenue should not be interpreted as profit. The estimated capital requirement is substantial, and the current analysis represents a preliminary techno-economic assessment rather than a complete investment appraisal. Actual profitability would depend on operating and maintenance expenditure, energy consumption, financing costs, equipment replacement, plant availability, product transportation, market demand, exchange-rate movements, taxation, and fluctuations in LPG prices. The economic values obtained in this study should therefore be treated as indicators of commercial potential rather than definitive evidence of financial profitability.

This distinction is particularly important for investment decisions. A technically feasible recovery process may not automatically remain economically attractive under unfavorable market or operating conditions. Future economic assessment should therefore incorporate discounted cash-flow indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), and discounted payback period, together with sensitivity and uncertainty analyses. Testing variations in LPG price, feed-gas availability, operating expenditure, exchange rate, and capital cost would provide a more reliable picture of the project's economic resilience.

D. Implications of the Integrated Approach

The broader contribution of the study lies in integrating feed characterization, process simulation, equipment sizing, hydrocarbon recovery, and preliminary economic evaluation within a single engineering framework. These dimensions are often evaluated independently, whereas their integration provides a clearer relationship between feed characteristics, separation performance, equipment requirements, recoverable products, and potential economic value. For flare-gas utilization in the Niger Delta, this integrated perspective is particularly relevant because implementation decisions cannot be based on product recovery alone. The feed must be technically suitable, the process configuration must achieve adequate separation, the equipment must accommodate the required throughput, and the recovered products must provide sufficient value to justify investment. The proposed framework therefore provides a practical basis for preliminary project screening and for identifying the parameters that require more detailed investigation before industrial deployment.

The results also suggest that the value proposition of flare-gas recovery should not be restricted to LPG alone. Simultaneous recovery of methane and ethane creates the possibility of integrating LPG production with power generation, industrial gas supply, or petrochemical applications. Such integration could improve overall hydrocarbon utilization and strengthen the economic justification of flare-reduction projects, although these alternative product pathways require separate market and infrastructure assessments.

E. Limitations of the Study

Several limitations should be considered when interpreting the findings. First, the study is based on process simulation and does not include pilot-scale or full-scale operational validation. Aspen HYSYS provides a useful engineering representation of the process, but actual plant performance may be affected by equipment inefficiencies, heat losses, pressure drops, fouling, control-system behavior, equipment turndown, and other operational conditions that are not fully captured in the model. The reported process performance should therefore be regarded as simulated rather than experimentally verified.

Second, relatively stable feed-gas composition and operating conditions were assumed. In actual flow-station operations, associated-gas composition and flow rate may vary over time because of changes in reservoir conditions and production operations. Such variability could influence dehydration requirements, refrigeration duty, column performance, product composition, and hydrocarbon recovery. Future simulations should therefore incorporate multiple feed scenarios and dynamic operating conditions to evaluate process robustness. Third, the economic analysis is preliminary and depends on simplified assumptions. It does not incorporate comprehensive operating expenditure, detailed maintenance costs, inflation, financing structure, discounted cash-flow analysis, or systematic uncertainty and sensitivity assessment. Consequently, the projected revenue and economic potential should not be interpreted as guaranteed commercial performance.

Finally, although the proposed process can reduce the volume of gas subjected to routine flaring, the study does not quantify its complete environmental footprint. Energy requirements for refrigeration, compression, pumping, and fractionation may generate indirect emissions that should be considered when determining net environmental benefits. Future research should therefore combine process simulation with lifecycle or emissions analysis, detailed techno-economic assessment, and pilot- or field-scale validation. Despite these limitations, the integrated analysis provides a useful engineering basis for further development of flare-gas recovery systems in the Niger Delta. The findings support continued investigation of LPG recovery as part of a broader strategy for improving associated-gas utilization, reducing routine flaring, and creating additional energy value from existing hydrocarbon resources.

VI. CONCLUSION AND RECOMMENDATION

This study evaluated the technical and preliminary economic feasibility of converting flared associated natural gas into Liquefied Petroleum Gas (LPG) through an integrated process

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involving Triethylene Glycol dehydration, cryogenic Natural Gas Liquids recovery, and staged hydrocarbon fractionation. Using Aspen HYSYS Version 3.2 with the Peng–Robinson Equation of State, a feed stream of 34.83 MMScfd was successfully simulated and separated into commercially relevant product streams. The process recovered approximately 25.10 MMScfd of methane, 4.01 MMScfd of ethane, and 3.87 MMScfd of LPG, with the LPG stream consisting predominantly of propane and butane. The estimated annual LPG production was approximately 74.96 million kg. These results indicate that flared gas in the Niger Delta has substantial potential for recovery and productive utilization rather than routine combustion.

The economic assessment further indicated an estimated annual LPG revenue of approximately ₦18.74 billion at an assumed selling price of ₦250/kg, compared with an estimated capital investment of approximately ₦40 billion. Taken together, the technical and economic results suggest that the proposed configuration has promising potential for flare-gas utilization while supporting improved hydrocarbon resource efficiency, domestic energy supply, and reduction of routine gas flaring. However, the economic results should be interpreted as preliminary indicators rather than definitive measures of commercial profitability because they are based on simulation outputs and simplifying assumptions regarding market prices, operating costs, taxation, exchange rates, and plant availability. Field-scale validation and a more comprehensive techno-economic assessment are therefore required before full industrial implementation.

Based on the findings, petroleum-producing companies operating in the Niger Delta should consider LPG recovery as one component of broader flare-gas utilization and reduction strategies. Regulatory authorities may also support implementation through policies and investment incentives that encourage the commercialization of associated gas rather than routine flaring. Particular attention should be given to the integration of LPG recovery facilities with existing gas-processing infrastructure to improve resource utilization and reduce additional development requirements.

Future studies should extend the present analysis through pilot-scale or industrial-scale validation of the simulated process and should examine the effects of variations in feed composition, operating conditions, and plant throughput on product recovery and process stability. More detailed economic evaluation is also recommended, including discounted cash-flow analysis, Net Present Value, Internal Rate of Return, sensitivity analysis, and uncertainty assessment under changes in LPG prices, exchange rates, operating expenditures, and capital costs. Further investigation of integrated utilization pathways for the recovered methane and ethane, including power generation and petrochemical applications, would provide a more complete assessment of the economic and environmental value of flare-gas recovery in Nigeria.

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DATA AVAILABILITY

The data used in this study were obtained from operational records and process reports from selected flow stations in the Niger Delta region of Nigeria. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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