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TECHNO-ECONOMIC ASSESSMENT OF THE POTENTIAL OF NIGERIAN CRUDES IN HYDRO-SKIMMING MODULAR REFINERY

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Abstract: The refining of crude oil is central to the petroleum value chain, yet Nigeria's dependence on conventional large-scale refineries has been hindered by infrastructural and economic challenges. Modular refineries have emerged as a flexible and cost-effective alternative; however, their predominant reliance on topping technology has resulted in high residue yields and systemic inefficiencies. This study evaluates the technical and economic feasibility of hydro-skimming modular refineries for Nigerian crude oils including Bonny Light, Bonny Medium, Qua Iboe, and Nigeria Brass. This was carried out using Aspen HYSYS simulations. The hydro-skimming process was modeled to assess product yields including off gases, liquefied petroleum gas (LPG), gasoline, jet fuel, wastewater, residue, and automotive gas oil (AGO). The Economic viability was analyzed through deterministic and stochastic models incorporating capital and operational expenditures, Net Present Value (NPV), Internal Rate of Return (IRR), and payback period. The highest yield of LPG (7.10 m^3/hr), and gasoline (69 m^3/hr) were obtained from Nigeria Brass, and that of the jet fuel (20.10 m^3/hr), and AGO (70.30 m^3/hr) was produced from Bonny Medium. The least yield of off gases (5.5E-08 m^3/hr), wastewater (5.40 m^3/hr), and residue (30.40 m^3/hr) were obtained from Bonny Light, Nigeria Brass and Qua Iboe, respectively. The result of the economic analysis shows a strong investment potential, with NPVs exceeding $300 million and IRRs above 140 % across crude types. The results demonstrate that hydro-skimming significantly reduces residue compared to topping units, enhances gasoline and diesel yields, and meets modern fuel quality standards. These findings highlight hydro-skimming modular refineries as a technically robust and financially viable pathway to strengthen Nigeria's energy security, reduce dependence on imports, and promote sustainable refining infrastructure

Keywords: Techno-Evaluation, Hydro-Skimming, Modular Refinery, crude oil, Simulation

1.0 Introduction

Oil refineries are massive facilities, which can process a hundred thousand to hundreds of thousands of barrels of crude oil per day. The majority of the conventional refineries are complex, capital-intensive plants that can handle hundreds of thousands of barrels of crude oil per day. As a result of the large capacity, most refinery units are not run in batches, but in a continuous mode, which keeps them in a steady state or almost steady state over months to years. This is due to its continuous operation and high capacity that makes process optimization and advanced process control very desirable. Each refinery is configured and assembled differently and mostly depending on its location, the products it wants to produce, and the economic factors (Sing, 2021; Olujobi et al., 2022; Searle and Malin; Basaka et al., 2023; Yang and Barton, 2015). These refineries take advantage of large infrastructure and high technologies to attain high efficiency and economies of scale, which are part of the large and incessant demand of petroleum products. Nevertheless, the changing nature of the international energy market and technological innovations have led to the emergence of another model of refineries: modular refineries. Modular refineries are smaller, flexible units as opposed to conventional refineries, which can be assembled and commissioned faster and at a lower cost. These refineries are constructed in a modular manner that enables them to be scaled and adapted to the changing production requirements and regional demands. The modular refineries are especially beneficial in remote or underdeveloped regions where it would be economically or logistically impossible to build large conventional refineries. The modular design enables flexibility in the scaling of operations either up or down depending on the demand and available resources. This flexibility renders modular refineries an economical option to augment the local fuel supply, improve energy security and economic growth through the provision of employment opportunities in construction, operation and maintenance. Moreover, the comparatively low environmental footprint and the possibility to be moved or expanded on demand make modular refineries a good alternative to the dynamic demands of the global energy market. Modular refining of crude oil is done using a number of technologies but the most prevalent technology is topping technology. The topping technology in petroleum refining is a simplified and cost effective refining process that is aimed at the initial distillation of crude oil to generate the necessary products including diesel, kerosene, naphtha, and liquefied petroleum gas (LPG) (Michael & Woyinbrakemi, 2022). This design is characterized by its cost-effectiveness and simplicity, which is why it can be used in smaller-scale refineries or as an initial stage of bigger refining processes (Idris et. al., 2018). Nevertheless, the topping technology has been reported with related problem of bottom product (residue) (Bello et. al., 2022; Mamadu et. al., 2019; Ogbon et. al., 2018; Adeloye, 2022). In a bid to reduce the problem of high residue production during petroleum refining, Forman et. al. (2014) recommended the use of hydro-skimming technology in modular refinery set ups. Hydro-skimming is a process that involves atmospheric distillation and hydrotreating to separate crude oil into major products- diesel, kerosene, naphtha and liquefied petroleum gas (LPG) and minimize the level of sulfur content and enhance the quality of products. The method is defined by its simplicity of operation, low cost, and scalability, which is why it is suitable in small-to-medium-scale refineries or a preliminary processing stage in large complexes.

The refining industry in Nigeria has progressively resorted to modular refineries to enhance local fuel production, reduce dependence on imports and boost local economies. Although modular systems have benefits, including fast deployment, reduced capital expenditure and flexibility, their widespread use of simplistic topping designs has created systemic inefficiencies. Research indicates that in Nigerian modular refineries, topping units produce up to 40 percent of residue of crude feedstock with less than 50 percent operational efficiency (Bello et al., 2022; Nwaozuru, 2014; Mamadu et al., 2019; Ogbon et al., 2018). Such high residue production reduces profitability as well as increases the environmental risks due to unsustainable waste disposal methods. In order to overcome these difficulties, it is essential to switch to hydro-skimming technology. Hydro-skimming provides a way to improve economic and environmental sustainability by maximizing the yield of products and reducing residue. Nevertheless, the suitability of this technology to the different types of crude in Nigeria, especially the light and sweet crudes such as Bonny Light and the heavy crude such as Forcados, is not well researched.

This study compares the technical feasibility (e.g. compatibility with Nigerian crude assays, yield profiles, and sulfur content) and economic feasibility (e.g. capital/operational costs, return on investment) of hydro-skimming technology in modular refinery designs in the context of Nigeria. The study will use crude-specific data and refinery performance indicators to give practical recommendations to the policy makers and investors, and eventually aid in the creation of efficient and sustainable refining infrastructure in Nigeria.

2.0 Materials and Methods

2.1 Material

The properties (API gravity, density, viscosity, sulfur and true boiling point) of the various crude oil including Bonny

Light (2011), Bonny Medium (1997), Qua Iboe (2013), Nigeria Brass (2012) are presented in Table 1.

The simulation was carried out using Aspen HYSYS (version 11)

Table 1. Crude oil assay data

S/N	Crude Types	API gravity	Density (kg/m^3)	Viscosity (cSt)	Sulfur content (%)	True Boiling Point (°C)
1.	Bonny Light (2011)	37 - 39	877.37	1.588	0.008	30 - 600
2.	Bonny Medium (1997)	29 - 31	886.41	7.107	0.189	40 - 650
3.	Qua Iboe (2013)	36 - 38	844.52	3.171	0.134	35 - 620
4.	Nigeria Brass (2012)	33 - 35	821.60	1.763	0.108	40 - 640

2.2 Methods

2.2.1 Technical Evaluation of Hydro-skimming for Nigerian Crude Types

Aspen HYSYS (Version 11) was used to simulate virtual models of the various refining technology that recreated the physical and chemical reactions that take place in a refinery, and it gave a digital twin that acted like a real-world system. This allowed the operational efficiency, product and residue production of the modular refining method to be analyzed in detail. This

Step 1

Define Simulation Basis

The fluid Package used was Peng-Robinson for hydrocarbon systems.

The units was set to SI unit.

Step 2

Crude Assay Input

Input the True Boiling Point (TBP) data or use Crude Assay Manager in HYSYS.

Step 3

Build the Hydro skimming Configuration

Create the following unit operations:

a) Crude Preheat Train: Heat exchangers to raise crude temperature before distillation.

b) Desalter (optional): Remove salts and water.

c) Atmospheric Distillation Column: Define trays or stages.

d) Product Coolers and Pumps: Cool and transfer products to storage.

Step 4

Run Simulation and Analyze Result

Simulation Process Explained

a) Crude Feed and Pump

Crude from storage is metered by a pump into the preheat train. In the HYSYS simulation, feed conditions are specified (temperature, pressure, flow rate) and apply the Peng-Robinson property package to represent hydrocarbon behavior.

b) Preheat Train

The feed passes through a series of heat exchangers (E-100 to E-103) where it recovers heat from product streams. In HYSYS, each exchanger block is defined by its hot and cold streams and a heat duty target. Convergence ensures energy balances satisfy specified duties.

c) Desalter

Salt and water are removed by washing with fresh water. A mixer is modeled, a settling vessel, and a decanter where entrained water separates. HYSYS tracks water-and-salt removal efficiency using split fractions and phase separation.

d) Furnace

Desalted crude is heated to about 350 °C. The heater block in HYSYS requires inlet/outlet temps and fuel gas flow. The software calculates duty and flue gas composition based on combustion reactions.

e) Atmospheric Distillation Column

This is the core separation unit. You specify:

- Number of stages
- Feed stage location
- Reflux ratio
- Overhead pressure

HYSYS solves material and energy balances across trays, yielding fraction compositions.

f) Overhead Condenser and Reflux Drum

Vapors from the top stage are condensed to liquid in the condenser block. The reflux drum separates liquid and uncondensed vapors. A condenser duty and drum pressure is set up; HYSYS returns refrigerant flow rates and phase splits.

g) Reflux Pump

A pump sends a portion of the condensed naphtha back to the top of the column. In HYSYS, a pump curve is defined or a simple head rise to meet reflux flow specifications.

h) Side Draws and Product Cooling

Kerosene and diesel are withdrawn on intermediate trays. Each side draw goes through a cooler and pump package. Target outlet temperatures are specified, and HYSYS calculates cooling duties and pump power requirements.

i) Bottoms (Atmospheric Residue)

Heavy residue exits the column bottom, is cooled, and sent to storage. The residue cooler is modeled similarly to the side-stream coolers, with HYSYS reporting duty and final product temperature.

2.2.2 Economic Evaluation of Hydro-skimming for Nigerian Crude Types

Both deterministic and stochastic models were applied to assess the economic viability of the technology. These models provided insights into cost implications, financial risks, and potential returns of the technology.

2.2.2.1 Deterministic Model Components

The deterministic model was performed on Microsoft Excel version 2016. The various financial tools, steps, and assumptions that were used to perform the financial viability of all the technologies are as follows:

1) Capital Expenditure (CAPEX)

The determination of each technology Capex was performed on Aspen HYSYS. Since, it is difficult to quantify certain Capex cost, land cost, construction cost, licensing cost, etc., the Capex component used in the study only included the various equipment cost. The costing of each equipment used in the modeling was performed using the economic model built into Aspen HYSYS. The equipment costing was performed after the technical modeling has been completed on Aspen HYSYS and models simulation converged. These costs included capital cost, equipment cost and equipment installation cost.

2) Operational Expenditure (OPEX)

Operating expenditure termed OPEX are direct cost incurred within a period (usually a year) and are associated with production (Echendu et al. 2018). Fixed, variable and feed costs were classified as follows:

a) Fixed Cost: this was determined using the operating cost specified in Aspen HYSYS for all the equipment used in modeling the simulation.

b) Variable Cost: This was the plant utility cost, and was determined in Aspen HYSYS.

c) Feed Cost: all the crude types were cost at the same price, \$80/barrel. This price was determined by adding a premium of \$5 to the international price of Brent crude as at January 4, 2025 which was \$75.

3) Investment Performance Indicators

The Economic viability of refinery was measured using different economic benchmarks, these indices were;

i) Net Present Value (NPV)

Screening projects were considered acceptable if their net present value (NPV) is more than zero at the hurdle rate, and rejected otherwise. When deciding between competing investment options, the one with the highest net present value (NPV) is the superior choice and was determined using Equation 1.

$$NPV= \sum_{t=0}^{K} NCFt/(1+r)^{t} \quad (1)$$

Where NCF is cash flow and r = discount rate, therefore
NPV= Present value of periodic cash inflows - present value of periodic cash outflows

For the study, the NPV of each technology was evaluated at two different scenarios (10 %, and 15 %) to cover the sensitivity analysis.

b) Cash Flow

A cash flow statement was computed for all the refinery. Certain assumptions were made in calculating the cash flow statements; below is the breakdown of the assumptions that was made for the refinery:

Feed capacity**:** the feed for the refinery was 30,000 bpd

Price of feeds**:** the price of all the crude types used was calculated as \$80/barrel. This price was determined by adding a premium of \$5 to the international price of Brent crude as at of January 4, 2025 which was \$75. Furthermore, the Demin water used for mixing was priced at \$3/ m^3 while steam was priced at \$2/ m^3

c) Internal Rate of Return (IRR)

Assuming that the current fiscal regime, which is characterised by the royalty rate, R, at which the net present value (NPV) is zero, the internal rate of return (IRR) is the value of the discount rate. Each refining technology has its internal rate of return (IRR) determined using Equation 2.

$$NPV= \sum_{t=1}^{K} \frac{NCFt}{(1+IRR)t} = 0 \quad (2)$$

Also, IRR was also calculated for each sensitivity scenario.

2.2.2.2 Sensitivity Analysis of The Economic Evaluation

The Monte Carlo simulations was performed in Oracle Crystal Ball to determine the outcomes of a set of randomly selected input variables on the technologies. The output of each input was documented, and the model final output was used as a probability distribution for all scenarios.

3.0 Results and Discussion

3.1 Technical Evaluation of Hydro-skimming for Nigerian Crude Types

Table 2. shows the simulated product yields for four Nigerian crude types: Bonny Light, Bonny Medium, Nigeria Brass, and Qua Iboe, processed using a hydro-skimming modular refinery setup. The table highlights how each crude type performs in producing seven major product streams: Off-gases, LPG, Gasoline, Jet Fuel, Wastewater, Residue, and Diesel (AGO).

Table 2. Product volume flow of all crude types using the hydro skimming modular configuration

Crude type	Off gases (m^3/hr.)	LPG (m^3/hr.)	Gasoline (m^3/hr.)	Jet Fuel (m^3/hr.)	Wastewater (m^3/hr.)	Residue (m^3/hr.)	AGO (m^3/hr.)
Bonny Light	5.5E-08	6.80	53.50	18.70	6.00	35.00	65.10
Bonny Medium	3.1E-06	5.30	36.20	20.10	5.50	42.10	70.30
Nigeria Brass	4.8E-06	7.10	69.00	14.90	5.40	30.40	44.20
Qua Iboe	2.1E-06	6.10	55.70	17.30	5.60	33.60	59.70

From Table 2, the quantity of off-gas generated is minimal in all four types of crude. Nigeria Brass releases the most off-gases of 4.8E-06 m^3/hr and Bonny Light releases the least of 5.5E-08 m^3/hr. The slightly greater off-gas of Nigeria Brass might be explained by the fact that it has more volatile compounds or lighter hydrocarbons. The small volume of the off-gas produced is consistent with the usual operation of hydro-skimming units, which are less sophisticated and release fewer volatile hydrocarbons than more sophisticated cracking design.

The Liquefied Petroleum Gas (LPG) production ranges between 5.30 m^3/hr for Bonny Medium, and 7.10 m^3/hr for Nigeria Brass (Table 2). The result show that the Nigeria Brass contains more lighter hydrocarbon molecules than the Bonny Light, Bonny Medium and Qua Iboe crudes, respectively. This is a high output considering the increasing applicability of LPG to residential energy requirements in sub-Saharan Africa. The high LPG production of the Nigerian Blass justifies previous results that this mixture has a higher percentage of lighter fractions which makes it more suitable in modular refining to provide domestic energy solutions. Nigeria Brass also did well in terms of gasoline with a yield of 69.00 m^3/hr, as compared to the Bonny Medium which had a yield of 36.20 m^3/hr.

The gasoline is among the major products, and its production was between 36.20 m^3/hr for the Bonny Medium, and 69.00 m^3/hr for the Nigeria Brass. The Nigeria Brass has a high yield of gasoline implying that it contains more naphtha-range hydrocarbons which can be reformed to Premium Motor Spirit (PMS) easily. Bonny Light and Qua Iboe are also effective in the production of gasoline and hence they are suitable in the modular refineries where the recovery

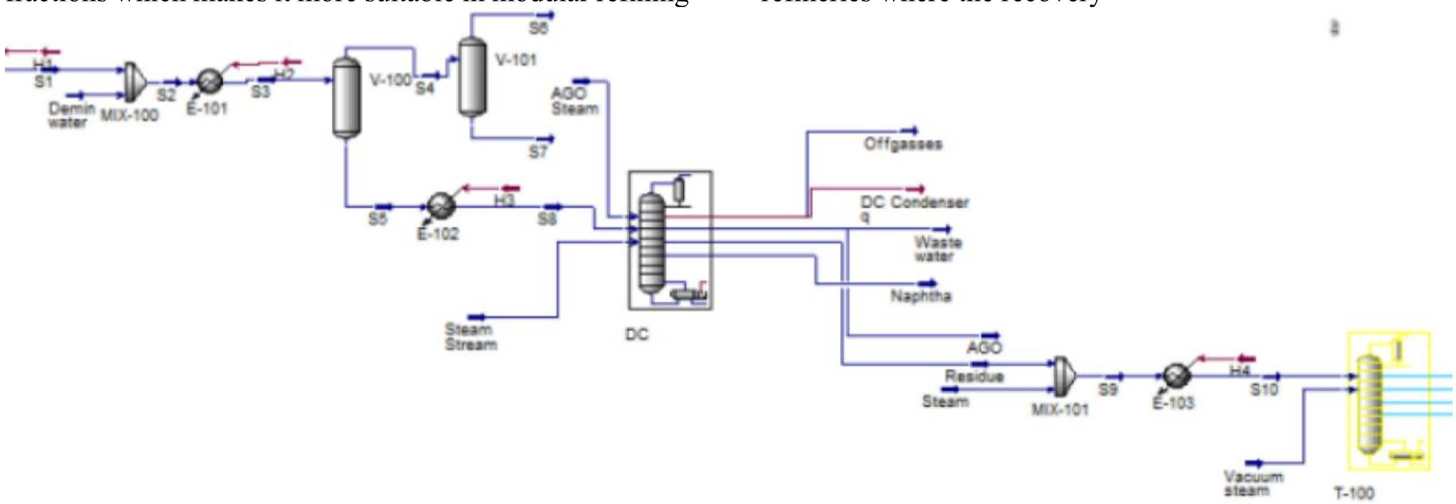

Figure 1. Process flow diagram of the separation of crude oil into fractions in the hydro skimming configuration of PMS is essential. The difference in yield is a measure of the differences in naphtha content and catalytic reforming ease of the crudes.

The quantity of the Jet fuel also known as Dual Purpose Kerosene (DPK) obtained was between 14.90 m^3/hr for the Nigeria Brass, and 20.10 m^3/hr for the Bonny Medium. Both Bonny Medium and Qua Iboe produced good quantities of jet fuel, hence can produce large amounts of kerosene fractions in line with its heavier, kerosene-rich profile, which is required in the production of aviation-grade fuel (Ehinomen & Adeleke, 2012). The production of jet fuel within the 12 - 15 % range of the total production also reflects the consistency with the general expectations of the hydro-skimming operations.

The hydro-treatment process produces wastewater with a range of 5.40 to 6.00 m^3/hr. Bonny Light has the greatest volume, The increased amount of wastewater can be explained by the fact that the hydro-treating of naphtha and AGO streams is more intensive, which is observed in previous refinery simulations with Bonny Light (Okoli and Aderibigbe, 2019). The manageable volumes imply that the environmental compliance is possible to be attained with the traditional treatment units incorporated into the modular system.

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The yield of residues is a very important parameter in the evaluation of refining efficiency. The heavy components of the crude that are not processed in the hydro-skimming facility was between 30.40 m^3/hr for the Nigeria Brass, and and 42.10 m^3/hr for the Bonny Medium. These are much lower than the traditional topping refineries which normally produce 65 -101 m^3/hr of residue. These values are significantly less than the 65 - 101 m^3/hr typically related to topping refineries, meaning that hydro-skimming improves the conversion ratio and reduces bottom-of-barrel fractions. This decrease, also indicates that hydro-skimming refineries are more effective in transforming crude oil into useful products. This helps the world to transition to cleaner and more efficient modular designs (IEA, 2022).

The diesel also known as the Automotive Gas Oil (AGO) is one of the most useful products in this simulation with a highest yield of 70.30 m^3/hr obtained from Bonny Medium, and lowest of 44.20 m^3/hr obtained from the Nigeria Brass. The result is in agreement with the findings by Okoro et al. (2020), who noted that Bonny Medium has a high middle distillate yield potential, and it should be used in diesel-focused refining processes. The yield contribution of AGO of 35 - 45 % highlights the correspondence of these crudes with the national energy consumption trends, in which diesel is the main fuel. Overall, the simulation shows that hydro-skimming modular refineries are technically viable to process all four Nigerian crudes, and Bonny Medium and Nigeria Brass, in particular, are characterized by good gasoline, diesel, and LPG yields. The findings are consistent with the recent studies that propose the use of modular refinery in Nigeria as a cost-efficient alternative to large-scale refineries.

3.2 Economic Evaluation of Hydro-skimming for Nigerian Crude Types

1) Deterministic Results

The deterministic financial models of modular refineries that process the four variants of Nigerian crude oil, Bonny Light, Qua Iboe, Nigeria Brass and Bonny Medium, gave strong long-term investment profiles (Tables 3 - 6). With a 20-year project life, both models have a start-up capital expenditure in the first two years, which is then followed by a constant revenue stream and operating costs. Such projections enable the thorough analysis of financial performance based on such key indicators as EBITDA (Earnings Before Interest, Taxes, Depreciation, and Amortization), corporate taxes, net cash flow, Net Present Value (NPV), and Internal Rate of Return (IRR). Corporate tax rate is 32 percent in all scenarios and NPVs are calculated at 10 percent and 15 percent discount rates to gain a comparative understanding.

The projected cash flow statement of Bonny light refinery model is presented in Table 3. The modular refinery will need an initial investment of $26.4 million in the first two years. Since year 3, it has been able to produce constant net revenues of around $2.023 billion annually, with its operating costs amounts to about $1.914 billion, which includes crude feedstock and utilities. This translates to a stable annual EBITDA of $108.4 million. The post-tax operating cash flow after taxation stands at $73.71 million dollars and the trend has been consistent throughout the 18 years of operation. The project provides NPV of $476.41 million at a discount rate of 10 percent and $319.67 million at a discount rate of 15 percent, and the IRR of 145 % is impressive, and the profitability is high.

The projected cash flow statement of Qua Iboe refinery model is contained in Table 4, and it shows an initial investment cost of $26.825 million. The initial annual net revenues are $2.152 billion, and the annual operating and utility expenses are approximately $2.016 billion. This generates an EBITDA of $136.46 million and a post-tax cash flow of $92.79 million, which is maintained during the operation period. In terms of financial, Qua Iboe has an NPV of $605.36 million at 10 percent and $407.74 million at 15 percent and an outstanding IRR of 168 %, which is the highest of the four models, indicating outstanding returns on investments compared to capital expenditure.

Nigeria Brass refinery will cost an initial investment of $26.636 million (Table 5). It begins to produce net revenues of $2.136 billion annually since year 3, and the operating costs remained stable at around $2.006 billion. This gives an annual EBITDA of $130.30 million, and post-tax net cash flow of $88.60 million. At 10 percent discount rate, the NPV of the project was $577.20 million and at 15 percent discount rate, the project had an NPV of $388.59 million with an IRR of 166 , a little lower than Qua Iboe refinery but still indicating a good profile of returns and long-term sustainability.

Finally, the Bonny Medium refinery model appears to be the most appealing in terms of finances. It has a similar start-up capital of $26.25 million and provides significantly greater net annual revenues of $2.961 billion. The highest operating costs are at $2.739 billion which translates to a healthy EBITDA of $221.89 million per year. The refinery will have a steady post-tax cash flow of $150.88 million after tax deductions, the highest in the group. The NPV of 10 percent discount rate is an impressive figure of $999.68 million, and 15 percent discount rate is $677.48 million with an impressive IRR of 236 %. These excellent measures underscore the high ability of Bonny Medium to produce cash flows, maximize returns of investments and resist economic changes. Overall, each of the four deterministic models has a financially viable scenario, with Bonny Medium having the highest profitability and return measures, closely followed by Qua Iboe and Nigeria Brass. Bonny Light is slightly less profitable, but it still shows good financial results. All these models highlight the economic potential of modular refineries that are specific to various Nigerian crude blends. This supports the earlier results of Michael et al. (2022), who highlighted that Bonny Medium and other light-to-medium Nigerian crude grades are best suited to modular refineries because of the higher distillate fractions and relatively low amounts of sulfur, which decreases the secondary processing requirements.

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Table 3: Projected cash flow statement of Bonny light refinery model

Year	Investment ($)	Net Revenues ($)	Cost of feed crude ($)	Operating Cost ($)	Utilities cost ($)	Total Operating Cost ($)	EBITDA ($)	Corporate Tax (@32%)	Operating cash flow ($)	Net cash flow ($)	NPV @	NPV @	IRR (%)
											10 %	15 %	
1	17,000,000					0			0	- 17,000,000	$476,409,736.55	$319,669,228.86	145
2	9,407,900					0			0	-9,407,900			
3		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			
4		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			
5		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			
6		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			
7		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			
8		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			
9		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			
10		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			
11		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			
12		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			
13		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			
14		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			
15		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			
16		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			
17		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			
18		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			
19		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			
20		2022510000	855550000	1051571000	6985200	1914106200	108,403,800	34689216	73,714,584	73,714,584			

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Table 4. Projected cash flow statement of Qua Iboe refinery model

Year	Investment ($)	Net Revenues ($MM)	Cost of feed crude ($)	Operating Cost ($)	Utilities cost ($)	Total Operating Cost ($)	EBITDA ($)	Corporate Tax (@32%)	Operating cash flow ($)	Net cash flow ($)	NPV @	NPV @	IRR (%)
											10%	15%	
1	-17,000,000					0			0	-17,000,000	$605,361,041.30	$407,743,719.34	168
2	-9,825,000					0			0	-9,825,000			
3		2152720000	877030000	1131502000	7731610	2016263610	136,456,390	43666045	92,790,345	92,790,345			
4		2152720000	877030000	1131502000	7731610	2016263610	136,456,390	43666045	92,790,345	92,790,345			
5		2152720000	877030000	1131502000	7731610	2016263610	136,456,390	43666045	92,790,345	92,790,345			
6		2152720000	877030000	1131502000	7731610	2016263610	136,456,390	43666045	92,790,345	92,790,345			
7		2152720000	877030000	1131502000	7731610	2016263610	136,456,390	43666045	92,790,345	92,790,345			
8		2152720000	877030000	1131502000	7731610	2016263610	136,456,390	43666045	92,790,345	92,790,345			
9		2152720000	877030000	1131502000	7731610	2016263610	136,456,390	43666045	92,790,345	92,790,345			
10		2152720000	877030000	1131502000	7731610	2016263610	136,456,390	43666045	92,790,345	92,790,345			
11		2152720000	877030000	1131502000	7731610	2016263610	136,456,390	43666045	92,790,345	92,790,345			
12		2152720000	877030000	1131502000	7731610	2016263610	136,456,390	43666045	92,790,345	92,790,345			
13		2152720000	877030000	1131502000	7731610	2016263610	136,456,390	43666045	92,790,345	92,790,345			
14		2152720000	877030000	1131502000	7731610	2016263610	136,456,390	43666045	92,790,345	92,790,345			
15		2152720000	877030000	1131502000	7731610	2016263610	136,456,390	43666045	92,790,345	92,790,345			
16		2152720000	877030000	1131502000	7731610	2016263610	136,456,390	43666045	92,790,345	92,790,345			
17		2152720000	877030000	1131502000	7731610	2016263610	136,456,390	43666045	92,790,345	92,790,345			

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Vol.13, No. 04; April-2026;
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Table 5. Projected cash flow statement of Nigeria Brass refinery model

Year	Investment	Net Revenues ($)	Cost of feed crude	Operating Cost	Utilities cost	Total Operating Cost	EBITDA	Corporate Tax (@32%)	Operating cash flow	Net cash flow	NPV @	NPV @
											10%	15%
1	-16,000,000					0			0	-16,000,000	$577,204,593.40	$388,588,326.49
2	-10,636,100					0			0	-10,636,100		
3		2136660000	877030000	1121565000	7769350	2006364350	130,295,650	41694608	88,601,042	88,601,042		
4		2136660000	877030000	1121565000	7769350	2006364350	130,295,650	41694608	88,601,042	88,601,042		
5		2136660000	877030000	1121565000	7769350	2006364350	130,295,650	41694608	88,601,042	88,601,042		
6		2136660000	877030000	1121565000	7769350	2006364350	130,295,650	41694608	88,601,042	88,601,042		
7		2136660000	877030000	1121565000	7769350	2006364350	130,295,650	41694608	88,601,042	88,601,042		
8		2136660000	877030000	1121565000	7769350	2006364350	130,295,650	41694608	88,601,042	88,601,042		
9		2136660000	877030000	1121565000	7769350	2006364350	130,295,650	41694608	88,601,042	88,601,042		
10		2136660000	877030000	1121565000	7769350	2006364350	130,295,650	41694608	88,601,042	88,601,042		
11		2136660000	877030000	1121565000	7769350	2006364350	130,295,650	41694608	88,601,042	88,601,042		
12		2136660000	877030000	1121565000	7769350	2006364350	130,295,650	41694608	88,601,042	88,601,042		
13		2136660000	877030000	1121565000	7769350	2006364350	130,295,650	41694608	88,601,042	88,601,042		
14		2136660000	877030000	1121565000	7769350	2006364350	130,295,650	41694608	88,601,042	88,601,042		
15		2136660000	877030000	1121565000	7769350	2006364350	130,295,650	41694608	88,601,042	88,601,042		

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Table 6. Projected cash flow statement of Bonny Medium refinery model

Year	Investment ($)	Net Revenues ($MM)	Cost of feed crude ($)	Operating Cost ($)	Utilities cost ($)	Total Operating Cost ($)	EBITDA ($)	Corporate Tax (@32%)	Operating cash flow ($)	Net cash flow ($)	NPV @	NPV @	IRR (%)
											10%	15%	
1	-16,000,000					0			0	-16,000,000	$999,676,933.27	$677,475,075.35	236
2	-10,246,610					0			0	-10,246,610			
3		2960840000	877030000	1851337000	10585870	2738952870	221,887,130	71003882	150,883,248	150,883,248			
4		2960840000	877030000	1851337000	10585870	2738952870	221,887,130	71003882	150,883,248	150,883,248			
5		2960840000	877030000	1851337000	10585870	2738952870	221,887,130	71003882	150,883,248	150,883,248			
6		2960840000	877030000	1851337000	10585870	2738952870	221,887,130	71003882	150,883,248	150,883,248			
7		2960840000	877030000	1851337000	10585870	2738952870	221,887,130	71003882	150,883,248	150,883,248			
8		2960840000	877030000	1851337000	10585870	2738952870	221,887,130	71003882	150,883,248	150,883,248			
9		2960840000	877030000	1851337000	10585870	2738952870	221,887,130	71003882	150,883,248	150,883,248			
10		2960840000	877030000	1851337000	10585870	2738952870	221,887,130	71003882	150,883,248	150,883,248			
11		2960840000	877030000	1851337000	10585870	2738952870	221,887,130	71003882	150,883,248	150,883,248			
12		2960840000	877030000	1851337000	10585870	2738952870	221,887,130	71003882	150,883,248	150,883,248			
13		2960840000	877030000	1851337000	10585870	2738952870	221,887,130	71003882	150,883,248	150,883,248			
14		2960840000	877030000	1851337000	10585870	2738952870	221,887,130	71003882	150,883,248	150,883,248			
15		2960840000	877030000	1851337000	10585870	2738952870	221,887,130	71003882	150,883,248	150,883,248			

2.2.2.2 Stochastic Model Components

Sensitivity Analysis of The Economic Evaluation

The sensitivity analysis was conducted using Monte Carlo simulations to evaluate how uncertainties in feedstock costs, operating expenses, and revenue fluctuations affect the financial viability of modular refinery projects processing four Nigerian crude oil types: Bonny Light, Nigerian Brass, Bonny Medium, and Qua Iboe. The result obtained are presented in Figures 2 - 4. As shown in Figure 2, the sensitivity analysis of the Internal Rate of Return (IRR) of all the crude oil variants shows that there are significant differences in economic performance in different operational conditions. Bonny Medium shows better performance under all the simulation conditions such as worst-case, mean, base case and best-case with high profitability, and resilience to the uncertainties in feedstock cost, operating expenditure and revenue changes. This consistency and strength highlights the Bonny Medium as the most economically feasible choice among the considered types of crude. On the other hand, Bonny Light has the lowest IRR in the worst-case scenario (31 %), which indicates a high level of sensitivity to unfavorable market conditions. This implies that the returns of Bonny Light are susceptible to cost and revenue fluctuations, thus, presenting a relatively greater financial risk. This was sensitive because of the comparatively low processing margins and reliance on international prices on light-end products. Conversely, Michael et al. (2022) analyzed financial models of modular refining projects in sub-Saharan Africa and found that the Nigerian Brass with intermediate properties offers a trade-off between the flexibility of processing and product yield. Their results indicated IRRs of 130-180 which is very close to the mean IRR of 149.8 of this study.

Both Nigerian Brass and Qua Iboe have more balanced IRR profiles, with their worst and best-case results being relatively close to each other (Figure 2). These findings indicate a moderate risk-return framework, which offers a trade-off between high yield and stability. The IRR ranges are relatively small, which means that the investment performance is less volatile and predictable.

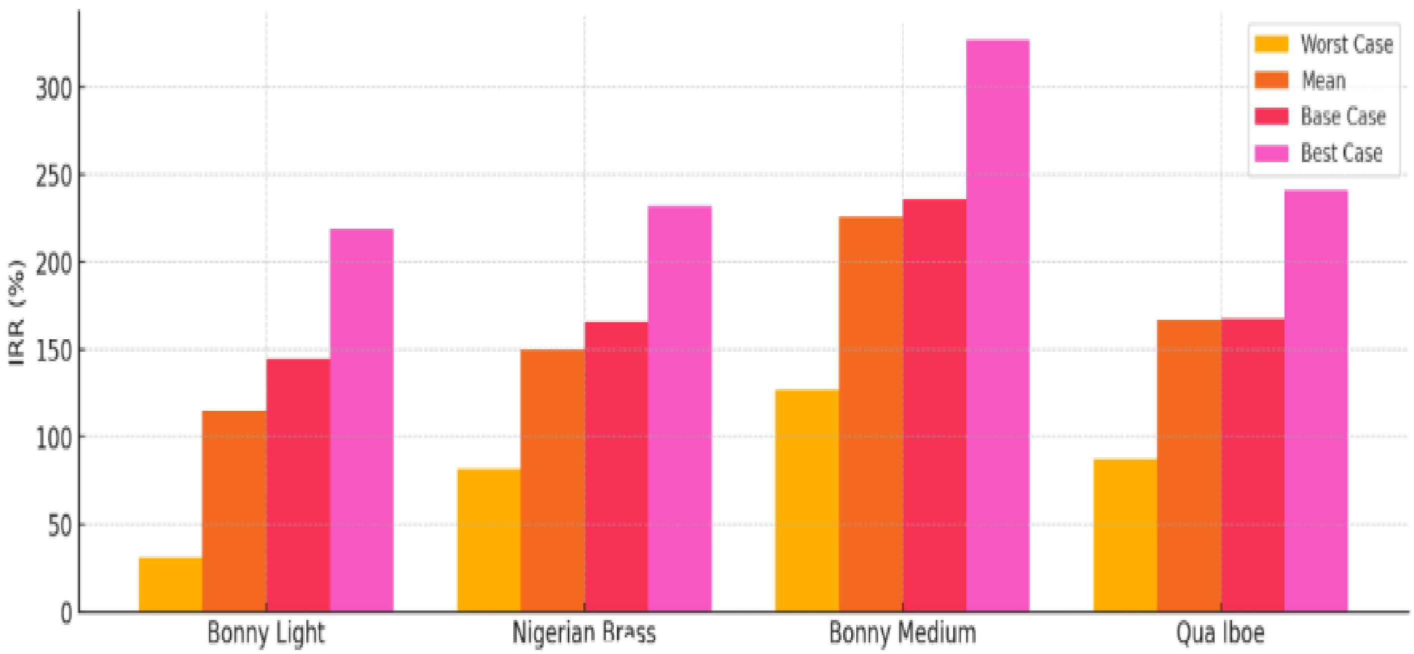

Figure 2. Sensitivity analysis of the Internal Rate of Return (IRR)

The result of the Net Present Value (NPV) at a discount rate of 10 percent is presented in Figure 3. The Bonny Medium shows the best performance with the highest mean NPV of the simulations. This is an indication of high ability to create long term value. Nigerian Brass and Qua Iboe are also highly profitable at this discount rate albeit to a smaller degree whereas Bonny Light is relatively lower in the mean values, which supports its claim as the weakest of the four in the case of financial stress. Moreover, Michael et al. (2022) reported NPV ranges were also similar and simulations generated consistent mean NPVs of over 500 million. The authors found that the profile of Nigerian Brass was a moderate risk-moderate return and this is consistent with the current interpretation.

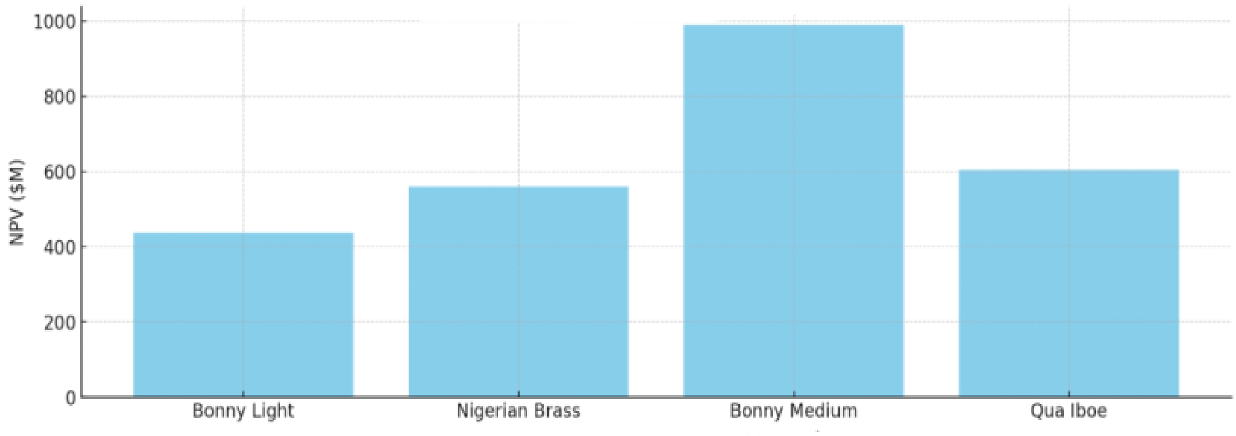

Figure 3. Sensitivity analysis of the NPV at 10 % discount rate

Figure 3. Sensitivity analysis of the Net Present Value (NPV) at 10 % discount rate

The pattern of performance is the same at 15 percent discount rate (Figure 4). Bonny Medium continues to be the leader in the mean NPV, which proves its ability to provide appealing returns even with more conservative investment assumptions. It is worth noting that Qua Iboe is a little bit more competitive than Nigerian Brass in this case, in terms of mean NPV, which implies that it is more competitive in a situation where future cash flows are more heavily discounted. In short, the sensitivity analysis supports the fact that Bonny Medium is the most economically sound and financially rewarding choice, which can withstand cost and revenue uncertainty without affecting profitability significantly. Nigerian Brass and Qua Iboe provide moderate but stable economic performance whereas Bonny Light, though having high upside when economic conditions are favorable, has a higher risk profile since it is highly sensitive to unfavorable economic variables.

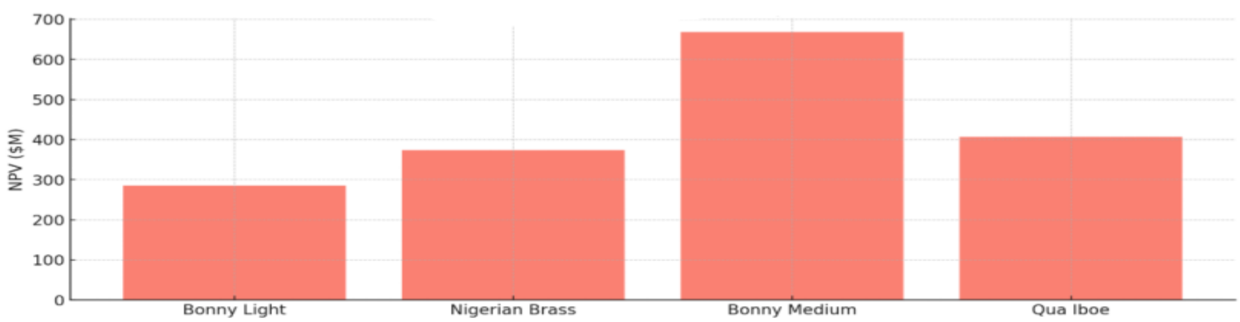

Figure 4. Sensitivity analysis of the NPV at 15 % discount rate

4. Conclusion

The technical analysis established that all the four types of Nigerian crude, especially Bonny Medium and Qua Iboe, can be used in hydro-skimming modular refinery setups, yielding high volumes of desirable petroleum products including naphtha, kerosene, gasoil, and atmospheric residue. Bonny Medium had the most balanced and higher production of middle distillates, which confirmed its technical compatibility with the hydro-skimming process. The ease of the hydro-skimming system enabled the efficient treatment of medium and light-sweet crudes which generally need less upgrading and produce higher value distillates. Economically, the deterministic financial models showed high profitability in all the types of crude. The most economically attractive alternative was Bonny Medium which produced the highest net annual revenue, EBITDA, post-tax cash flow and Net Present Value in the 20-year period. It has an impressive Internal Rate of Return of 236 % and this indicates that it recovers its capital fast and remains profitable.

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