Volume 10, Issue 3, March– 2025 International Journal of Innovative Science and Research Technology
ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25mar031

Economic Analysis of Heat Exchanger for a Simple Cycle Gas Turbine Power Plant

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Publication Date: 2025/03/20

Abstract: This study undertakes a comprehensive economic analysis of integrating a heat exchanger with a simple cycle gas turbine power plant, with a specific focus on the Siemens SGT5-2000E gas turbine model. The analysis leverages on key parameters such as Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PBP) and Levelized Cost of Electricity (LCOE), to evaluate the viability and profitability of the investment. The results of the analysis show that integrating a heat exchanger with the gas turbine power plant yields a positive NPV of ₦166,031,518.3, signifying that the investment is profitable. Furthermore, the IRR is approximately 12.22 %, which is the discount rate at which the NPV becomes zero. The payback period is determined to be 7.7 years, indicating that the investment will break-even within a reasonable timeframe. Additionally, the levelized cost of electricity is calculated to be ₦65.23/kWh, which corresponds to a discount rate of 55 %. The findings of this study provide valuable insights for investors, policymakers, and plant operators seeking to optimize the efficiency and competitiveness of gas turbine power plants. Overall, the results suggest that integrating a heat exchanger with a simple cycle gas turbine power plant is a viable and profitable investment opportunity.

Keywords: *Economic Analysis, Heat Exchanger, Simple Cycle Gas Turbine, Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PBP), Levelized Cost of Electricity (LCOE), Power Plant*

How to Cite: Isiaka Isah; Mohammed Sani Umar; Muhammad Masin Muhammad; (2025), Economic Analysis of Heat Exchanger for a Simple Cycle Gas Turbine Power Plant. *International Journal of Innovative Science and Research Technology*, 10(3), 402-408. https://doi.org/10.38124/ijisrt/25mar031

I. INTRODUCTION

Shell and tube heat exchanger is a type of heat exchanger that consists of a shell with a series of tubes inside it. It is one of the most common types of heat exchangers widely used in the industrial processes. It allows flow of fluid through the tubes, while another fluid flows over the tubes, allowing heat transfer from one fluid to the other. Ease of manufacture and layout of flow configurations are some of the important features of shell and tube heat exchanger over other types in the process industry for waste heat recovery and other applications[1]. There have been several studies on economic analysis of shell and tube heat exchangers for a simple cycle gas turbine power plant. However, more investigations need to be conducted especially on the Siemens gas turbine model SGT5-2000E located in Geregu power plant Kogi State, Nigeria for optimization and efficiency. Heat transfer rate in shell and tube heat exchanger depends on several factors such as inlet temperatures of fluids into the heat exchanger, tube diameter, shell diameter, a number of tubes, and baffle spacing. [2] presented paper on advancements in heat exchanger design for waste heat recovery in industrial processes. [3] analyze study of shell and tube heat exchanger for clough company with different parameters to improve the design. [1] carried out performance analysis of shell and tube heat exchanger, considering the parametric study to investigate effect of shell diameter and tube length on heat transfer coefficient and pressure drop for shell side with both triangular and square pitches. [4] presented paper on shell and tube heat exchanger flexible design strategy for process operability and considered flexibility index in the optimization procedure can improve the STHE design operability under the expected range of disturbance factors and lower the total cost. [5] conducted comprehensive review of heat transfer enhancement of heat exchanger, heat pipe and electronic components using graphene, and found out various applications of graphene in different types of heat exchangers and electronic devices. [6] studied the shell and tube heat exchanger with the effect of types of baffles and discovered that helical baffles have advantages over the other ones. [7] reviewed the design of shell and tube heat exchangers and used some analytical techniques such as log mean temperature difference (LMTD) and effectiveness-number of transfer units (ε-NTU) which gave same results. [8] presented paper on shell and tube heat exchanger considering the heat transfer area design process using various design calculations. [9] presented heat transfer analysis in counter flow shell and tube heat exchanger using design of experiments via Taguchi L9 orthogonal array showing baffle

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25mar031

plate thickness to be highly significant factors amongst three parameters considered for the experiment. [10] identified model nonlinear of the four heat exchanger types using mathematical models of dynamic system to measure the input and output signal of the real system. [11] conducted analysis of a high-temperature heat exchanger for an externally-fired micro gas turbine. MATLAB and Aspen Plus software were used for the analysis and results obtained show that the effectiveness of the corrugated plate heat exchanger is more influenced at larger thicknesses of deposit materials than the two-tube-passes shell and tube heat exchanger. [12] presented paper on the heat exchanger design and optimization by using generic algorithm for externally fired micro-turbine. MATLAB and FRONTIER were used to build code and optimization through multi-objective maximize the overall heat transfer coefficient and minimize both costs and pressure drops across the equipment. [13] investigated the effects of shell diameter on heat transfer performance in the shell-and-tube heat exchangers. CFD was used to simulate the flow and heat transfer in the heat exchanger results from the study show that the heat transfer coefficient increases with increasing shell diameter, the pressure drop decreases with increasing shell diameter and the overall heat transfer performance is optimized at a shell diameter of 0.3 to 0.4 m. [14] investigated the effect of mass flow rate on the performance of a shell and tube heat exchanger using numerical model for simulating the heat transfer and flow of fluid in the heat exchanger. The simulated results show that increasing the mass flow rate enhances the heat transfer coefficient, but also increases the pressure drop. [15] presented paper on performance of a high-temperature particle-based shell and tube crossflow heat exchanger suitable for CSP power generation application. Experiment was performed through thermal evaluation of a pilot 50 kW moving packed-bed particle-to-air heat exchanger. The results obtained from the work show high values of the overall heat transfer coefficient (up to ~120 $W/m^2°C$) in accordance with shell-and-tube indirect contact heat exchangers. [16] presented a computer program for designing shell-and-tube heat exchangers. Computer codes for design are organized to vary systematically the exchanger parameters such as, shell diameter, baffle spacing, number of tube-side pass to identify configurations that satisfy the specified heat transfer and pressure drops. [17] presented a new design approach for shell-and-tube heat exchangers using imperialist competitive algorithm (ICA) from economic point of view. Key design variables optimized include tube length, tube outer diameter, pitch size and baffle spacing, and results of the study show that a comprehensive computer code was developed to implement the proposed method and test cases demonstrated the algorithm's effectiveness and accuracy. [18] conducted an experimental investigation of heat transfer enhancement for a shell-and-tube heat exchanger and finding from the study showed heat transfer coefficient through shell-side coefficient increased by 18.2-25.5%, overall heat transfer coefficient increased by 15.6-19.7%, exergy efficiency increased by 12.9-14.1%, pressure losses increased by 44.6-48.8%, but with negligible impact on required pump power. [19] presented study on design and construction of a shell and tube heat exchanger for laboratory use. Bell-Delaware method was used for the study and results obtained show heat load was 107.973 kW, temperature changes for cold fluid was +10 ℃, hot fluid was -55 ℃ (to 45 ℃), pressure drops within allowable range, overall heat transfer coefficient was 134.23 W/m^2K and system efficiency was 73.3%. [20] designed a shell and tube heat exchanger utilizing MATLAB and AutoCAD software for calculations and found out that computer program was useful for designing and modifying shell-and-tube heat exchangers. [21] conducted a combined cycle thermo-economic analysis of a heat recovery steam generator, finding a 51.5 MW increase in power output and a 41.85% overall combined efficiency. [22] performed a thermoeconomic analysis to optimize steam pressure in a combined cycle gas turbine, developing a model that minimized power generation costs. [23] conducted a thermoeconomic analysis of steam-injected gas turbine cycles, finding that steam temperature increased with decreasing stack gas temperature. [24] evaluated the energy and exergy of a Nigerian thermal power plant, identifying the boiler and turbines as the primary sources of energy destruction. [25] analyzed the energy efficiency of a gas turbine power plant, finding that increasing turbine inlet temperature improved exergy efficiency. [26] examined the performance of an SGT5-2000E gas turbine power plant, finding an average net thermal efficiency of 30.21%. [27] compared the performance of various gas turbine topologies, finding that retrofitted cycles outperformed traditional simple cycles. [28] conducted a techno-economic analysis of gas turbine integration, finding that combining models increased power output and efficiency. [29] optimized a combined cycle power plant, developing a model that minimized total costs. [30] performed exergoeconomic and environmental analyses of a combined cycle power plant, finding a 5.63% reduction in CO_2 emissions and a 6% gain in energy efficiency.

This present paper will conduct economic analysis of shell and tube heat exchanger for a simple cycle gas turbine power plant base on economic metrics which include the Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PBP) and Levelized Cost of Electricity (LCOE).

II. METHODOLOGY

The methodology employed in conducting economic analysis of heat exchanger integrated with simple cycle gas turbine power plant involves assessing financial viability and economic performance of the plant. It exposes the investors to what the proposed investment would entails in terms of finances or funds and how to source and acquire them to execute the project. It equally exposes the possible challenges and risks that the investment would be faced with in the future and the period it will take the project to recoup all its capital investment. Integrating a heat exchanger with the simple cycle gas turbine serves as a means to reduce the operating costs of the power plant as it eliminates the need to pay penalties that may be imposed by regulatory authorities for emitting pollutants into the environment. In many countries, power plants are subject to financial penalties for releasing waste heat into the atmosphere thereby contributing to climate change and global warming. The economic analysis for the present study uses economic indices such as Net Present Value (NPV), Payback Period (PBP), Internal Rate of Return (IRR), and Levelized Cost of Electricity (LCOE) which were computed manually. The input data for

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25mar031

the SGT5-2000E gas turbine model used for the study was obtained from Geregu gas turbine power plant in Kogi State as shown in Table 1.

Table 1 Design Data of SGT5-2000E Gas Turbine

S/No	Parameters	Values	Units
1	Ambient temperature	288	K
2	Compressor outlet temperature	623	K
3	Turbine inlet temperature	1333	K
4	Exhaust temperature	813	K
7	Compressor pressure ratio	11:1	
8	Turbine pressure ratio	1:11	
9	Power output	145	MW
10	Mass flow of air	500	kg/s
11	Mass flow of gas	8	kg/s
12	Specific heat ratio	1.4	
13	Specific heat capacity of air	1.005	kJ/kgK
14	Specific heat capacity of air	1.14	kJ/kgK
15	LHV of NG	47,976.5[25]	kJ/kg

Similarly, for the economic analysis, equations were used for economic metrics such as the Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PBP) and Levelized Cost of Electricity (LCOE), and assumptions were made for other economic parameters which could be calculated. The Fig. 1 shows the shell and tube heat exchange considered for the study.

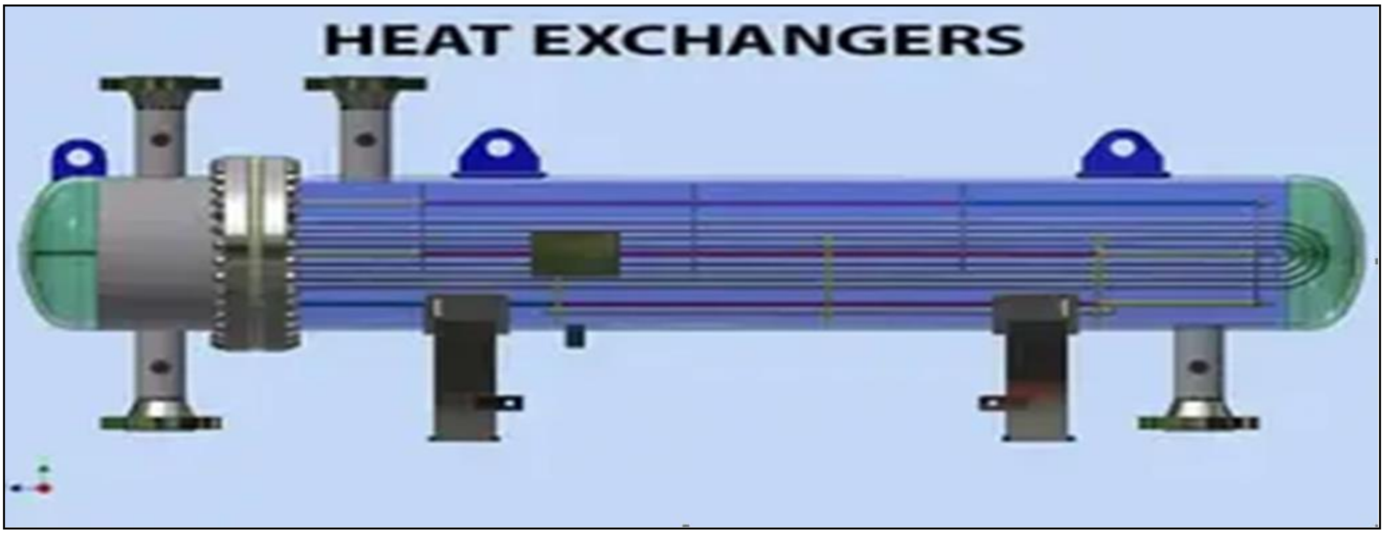

Fig 1 Shell and Tube Heat Exchanger [31]

➢ *Net Present Value (NPV)*

$$NPV = \Sigma\ PV - I \quad (1)$$

- Where;

$$PV = \text{Present Value and } = \frac{CF}{(1+r)^t} \quad (2)$$

Where; CF = Cash Flow, r = Discount Rate, t = Number of Period and I = Investment Cost.

➢ *Payback Period (PBP)*

Payback period is the time it takes for an investment to break even.

$$PBP = \frac{\text{Total Investment}}{\text{Annual Cash Flow}} \quad (3)$$

Where; Annual Cash Flow = Operating Cost Savings + Revenue

➢ *Internal Rate of Return (IRR)*

This is used to determine the overall projected profit of the investment. It is a discount rate that makes the NPV equal to zero.

- $$IRR = \left(\frac{CF0}{CF1 + CF2 + \cdots + CFn}\right)^{(1/n)-1} \quad (4)$$

Where; CF0 = Initial Investment (negetive cash flow), CF1, CF2,…., CFn = positive cash flows, n = Number of Periods

➢ *Levelized Cost of Electricity (LCOE)*

This is the measure of avearge electricity generating cost of one unit electricity (kWh) over the lifetime of the power plant.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25mar031

$$\text{Levelizd Cost of Electricity} = \frac{\text{Levelized Annual Costs}}{\text{Annual Amount of Power Generated}} \quad (5)$$

Where;

Levelized Annual Costs = [Initial investment cost x CRF] + Operations & Maintaenatce + Fuel cost + other costs

Annual Amount of Power Genearted = Total energy output over the project's lifetime

- CRF = Capital Recover Factor $= \frac{((i \times (1-i)^{n})}{(1+i)^{n}-1}$ (5)

Where; i = interest rate, and n = project's lifetime.

Assuming operations & maintenance (O&M) costs cover fuel cost and others costs, and equals 20 % of initial investment cost, discounted rate of 10 %, inflation rate of 34.80 %[32] and plant total life cycle of 15 years employed in the economic analysis. Other key inputs used in conducting this analysis are listed in Table 2.

Table 2 Assumptions for Economic Analysis Parameters

S/No	Economic parameters	Values	Units
1	Investment cost	100,000,000 (assume exchange rate of $1 = ₦1,500)	₦
2	Operations & maintenance cost	20 % of investment cost	₦
3	Inflation rate (as at December, 2024)	34.80 [146]	%
4	Interest rate (as at September, 2024)	27.25 [148]	%
5	Yearly operating hour	6456	h/y
6	Discount rate	10 %	
7	Plant's working life	15	Year
8	Capacity factor	90	%
9	Power	145	MW

III. RESULTS AND DISCUSSION

The results of the economic analysis of the investment are presented in this section. The analysis includes the Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PBP) and Levelized Cost of Electricity (LCOE). These metrics provide insights into the profitability, viability and competiveness of integrating the heat exchanger with the gas turbine. The net present value NPV of ₦166,031,518.3 as shown in Table 3 indicated that the investment is profitable, considering the effects of inflation rate of 34.80 %. The first column represents year of the project, starting from initial investment, 0 to year 15. Annual cash flow is in second column, and cumulative cash flow, inflation rate, net present value is respectively in columns three, four and five. Similarly, the Payback Period (PBP) for the investment can be found from the Table 3. The table shows the Cumulative Cash Flow (CCF) over 15 years, with the initial investment being inferred to be negative, as the CCF starts from 0. The cash flow pattern increases steadily over the years indicating a positive cash flow.

Table 3 Results of Cash Flow Analysis

Year	Annual cash flow	CCF	Inflation rate = 34.8 %		NPV
0	100,000,000	0			
1	10,000,000	10,000,000	10,000,000	1.329787234	7520000
2	12,000,000	22,000,000	16,176,000	1.768334088	12441088
3	15,000,000	37,000,000	27,256,560	2.351508096	15734583.3
4	17,000,000	54,000,000	41,640,755	3.127005446	17268917.8
5	18,000,000	72,000,000	59,433,605	4.158251923	17314968.24
6	19,000,000	91,000,000	84,567,416	5.529590323	16456915.37
7	20,000,000	111,000,000	119,996,713	7.353178621	15095512.53
8	20,000,000	131,000,000	161,755,569	9.77816306	13397199.37
9	20,000,000	151,000,000	218,046,507	13.00287641	11612815.14
10	20,000,000	171,000,000	293,926,691	17.29105906	9889504.133
11	20,000,000	191,000,000	396,213,179	22.9934296	8306720.805
12	20,000,000	211,000,000	534,095,366	30.57636914	6900753.945
13	20,000,000	231,000,000	719,960,553	40.66006535	5681250.092
14	20,000,000	251,000,000	970,506,826	54.06923584	4642196.179
15	20,000,000	271,000,000	1,308,243,201	71.90057957	3769093.401
	NPV				166031518.3

The cash flow analysis shows that the investment has a positive annual cash flow with a cumulative cash flow that increases steadily over the 15-year period. The inflation rate of 34.80 % was taken into account in the analysis.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25mar031

Table 4 Results of IRR

Discount Rate (%)	NPV
0%	171,000,000
5%	81,000,000
10%	4,787,910.99
15%	-4,226,921.51
20%	-25,858,366.94
25%	-98,342,572
30%	-146,236,938

The Table 4 presents a sensitivity analysis of the Internal Rate of Return (IRR) for the investment showing the Net Present Value (NPV) at different discount rates. The table shows the NPV at different discount rates, ranging from 0 % to 30 %. The NPV on the other hand decreases as the discount rate increases, indicating that higher discount rate reduces the present value of the project's cash flows. And the estimated IRR is approximately 12 %, as the NPV changes sign from positive to negative within the range or as the NPV becomes zero shown in Fig. 2 which is indicated with dashed line.

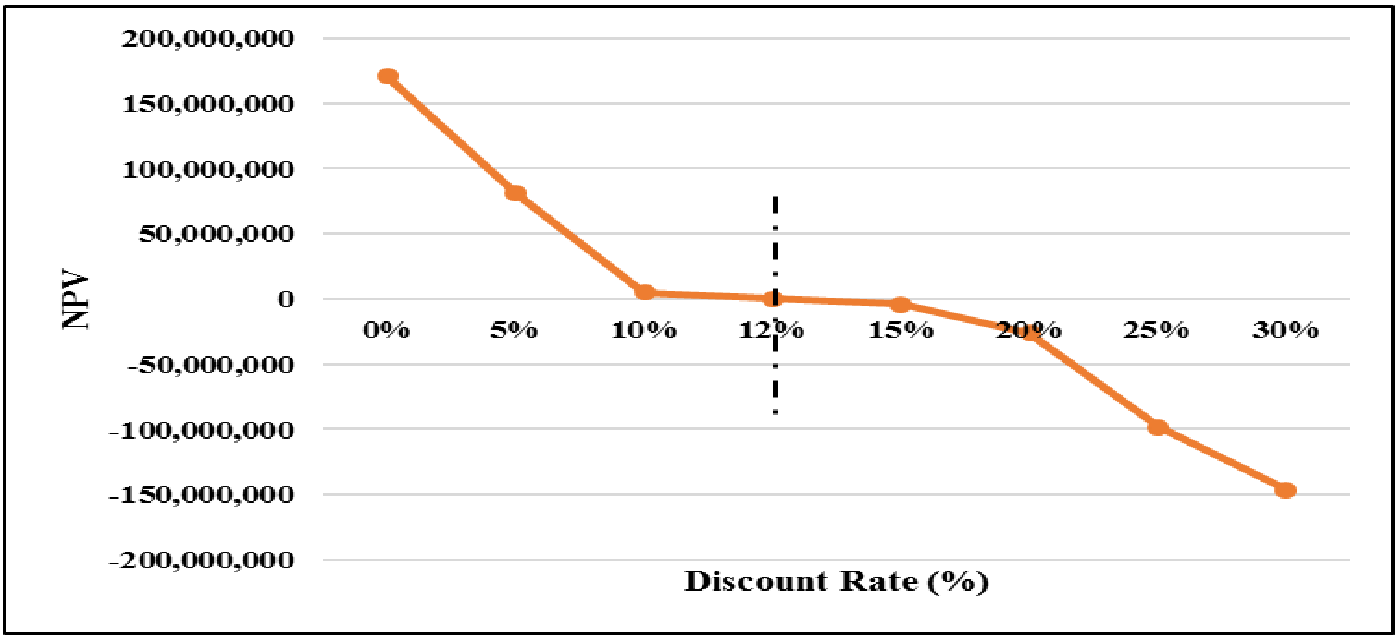

Fig 2 Net Present Value (NPV) and Internal Rate of Return (IRR)

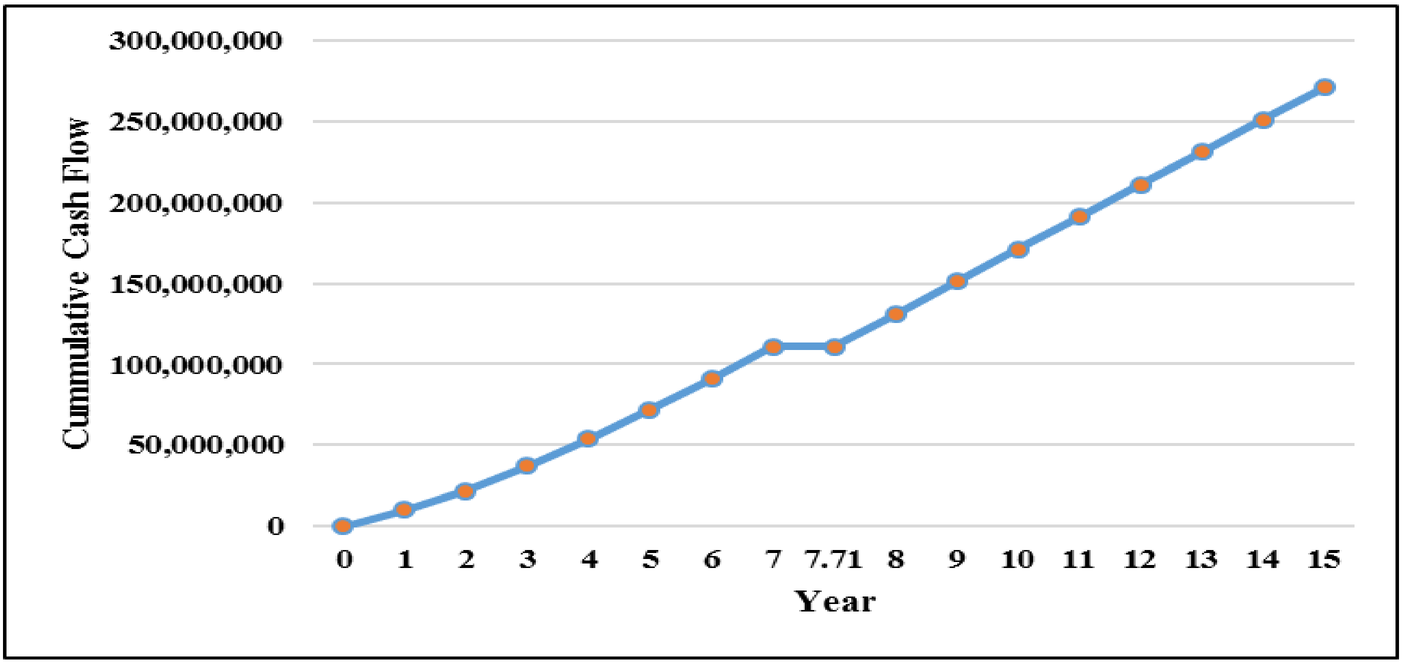

Fig 3 Payback Period

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25mar031

The Fig. 3 presents Payback Period for the investment. It can be shown from the figure that the investment has a Payback Period (PBP) of 7.7 years, indicating that it will take 7.7 years for the cummulative cash flow to become positive and for the investment to break even also.

Table 5 Results of LCOE

Discount Rate (%)	**LCOE (₦/MWh)**
0 %	0
5 %	5.934661748
10 %	11.8693235
15 %	17.80398524
20 %	23.73864699
25 %	29.67330874
30 %	35.60797049
35 %	41.54263224
40 %	47.47729398
45 %	53.41195573
50 %	59.34661748
55 %	65.28127923
60 %	71.21594098

The Table 5 presents the results of Levelized Cost of Electricity (LCOE) for the project. It can be observed from the table that the LCOE and discount rates, all have their values ranging from 0 % to 60 % and ₦0/kWh to ₦71.22/kWh respectively. However, the LCOE for the present work is ₦65.23/kWh coinciding with the discount rate at 55 %. Also, the LCOE also increases steadily as the discount rate increases, indicating that higher discount rates results in higher LCOE values.

IV. CONCLUSION AND RECOMMENDATIONS

➢ *Conclusion*

The economic analysis of integrating a heat exchanger with a simple cycle gas turbine power plant indicates that the investment is profitable and viable. The positive NPV, IRR, and relatively short payback period suggest that the investment will generate returns and break even within a reasonable timeframe. The levelized cost of electricity is competitive, indicating that the power plant can generate electricity at a reasonable cost.

➢ *Recommendations*

The recommendations drawn from the study are as follows:

- The investors and stakeholder should consider integrating heat exchangers with simple cycle gas turbine power plants as a viable investment opportunity.
- Further studies should be conducted to explore the technical feasibility and optimization of heat exchanger integration with gas turbine power plants
- Policy makers and regulators should consider providing incentives and support for investments in heat exchanger integration with gas turbine power plants to promote sustainable and efficient power generation
- Plant operators and managers should consider implementing heat exchanger integration with gas turbine power plants to improve efficiency, reduce costs, and increase competitiveness.

V. ACKNOWLEGMENT

The authors appreciate the staff and management of Geregu II Gas Turbine Power Plant for providing data for the study.

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