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Economic Evaluation of a Combined Cycle Gas Turbine Power Plant Integrated with an Absorption Chiller

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Abstract - This research shows the study of an economic evaluation and to investigate the economic acceptability and profitability of a combined cycle gas turbine power plant integrated with an absorption chiller, where the waste heat is used to power an absorption chiller to produce cooling for inlet air entering the compressor of a gas turbine on high ambient temperature days. Combined cycle gas turbine power plant attains a maximum power of 51.6 MW and efficiency of 52.8% when operated at ambient temperature of 47 °C with pre-cooling temperature of 10 °C applied to the compressor intake air.

The study further assesses the economic viability of the integrated power plant by analyzing its payback period (PBP), internal rate of return (IRR), profitability index (PI), and net present value (NPV). A Microsoft Excel model has been developed to compute the total capital investment cost, annual cash inflow, and annual cash outflow, facilitating the evaluation of the four criteria.

The findings indicate that the power plant is economically viable and profitable, with a payback period not exceeding 4.5 years, a profitability index of up to 1.60, an internal rate of return of 20.13%, and a net present value of approximately 39 million pounds.

***Key Words*:** Thermal design; ESDU; Economic evaluation; Li-Br absorption chiller; Combined cycle power plant; IPSEpro software

1. INTRODUCTION

Energy producing systems must be effectively managed to deliver the energy to the right place at the lowest financial and environmental cost.

Modern power plants have been designed to realize a product with a low initial investment cost and high efficiency so that the final product lifetime costs are minimized and the design is competitive in the market place.

The economic analysis represents a very important tool to study and optimize an energy system. This analysis has significant importance to realize the optimum market price of the product and to maximize the benefit. The objective of this research is to produce an economic evaluation of the energy system studied in order to reduce the costs and calculate the annual saving when the complete system operates at full load.

This research explores the economic viability of the proposed power plant by assessing its payback period (PBP), internal rate of return (IRR), profitability index (PI), and net present value (NPV). While fuel prices can fluctuate significantly, impacting the accuracy of the results, conducting this study is essential to illustrate the profitability and acceptability of the project, at least for the current context.

Initially, the capital cost for each subsystem or piece of equipment is either being calculated or sourced from official references and previous studies. This information is then used to determine the overall capital cost, encompassing all direct cost elements. Next, the annual cash outflow is calculated based on fuel costs and operational and maintenance expenses. Subsequently, the annual cash inflow is assessed according to the selling prices of the products, specifically electric power and cooling output. Finally, the economic acceptability criteria are applied to estimate the power plant under ISO conditions.

To conclude, several sensitivity analyses will be conducted to examine the impact of variable factors such as fuel charges, product vending bills, interest rates, and project lifespan on the overall project's economical performance.

2. INITIAL COST ESTIMATE

The initial financial cost refers solely to the apparatus purchase expenses. While this data can fluctuate over time, the objective was to gain it directly from vendor quotations or to select the latest figures from past purchase orders or studies. Otherwise, costs were estimated using the databases maintained by engineering firms. In the upcoming sections, each piece of equipment and system will be addressed individually, beginning with the methodology for approximating the initial charge of heat exchangers, followed by the preliminary charges of other systems, including the combined cycle gas turbine power plant and the single-effect water-lithium bromide absorption chiller (Figure 1).

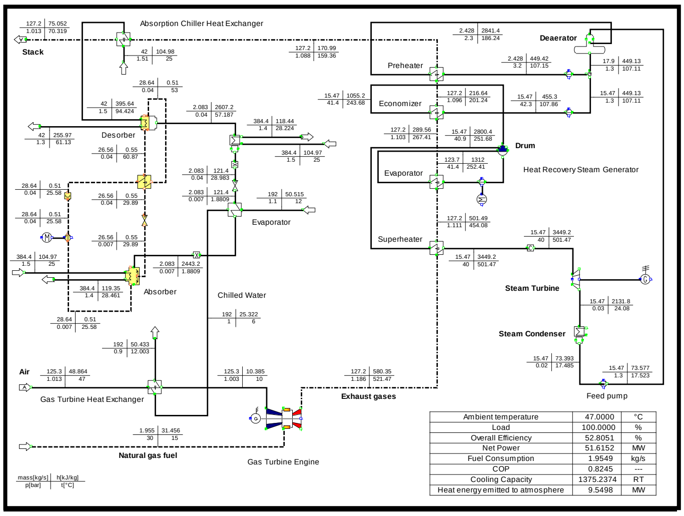


Table -1: Single-shaft combined cycle power plant connected with single effect absorption chiller modelled by IPSEpro

2.1 GAS TURBINE HEAT EXCHANGER

The preliminary charge of the heat exchangers was determined using the IHS (ESDU) international costing technique (Gregory et al., [3]). ESDU was collaborated with leading UK heat exchanger manufacturers, such as IMI Marston Ltd, to develop tables and curves that specify costs of heat exchanger per unit surface area. These resources were utilized to derive the C-values necessary for cost estimation.

To calculate the initial cost of the gas turbine air-intake cooler, the cooling load and the hot and cold side temperatures

To calculate the initial cost of the gas turbine air-intake cooler, first the cooling load ($\dot{Q}$) and the temperatures of hot and cold side are easily obtained via the IPSEpro simulation. The logarithmic mean temperature difference is then calculated using the following equation:

$$\Delta T_{lm} = \frac{[(T_{h,\ in} - T_{c,\ out}) - (T_{h,\ out} - T_{c,\ in})]}{\log_e [(T_{h,\ in} - T_{c,\ out})/(T_{h,\ out} - T_{c,\ in})]}$$

$$= \frac{[(15 - 6.795) - (10 - 6)]}{\log_e [(15 - 6.795)/(10 - 6)]} = 5.8529 \text{ K}$$

The cooling load $\dot{Q}$ = 633174 W
(from IPSEpro simulation software)

Since $\Delta T_m = \Delta T_{lm}$ for the double-pipe heat exchanger, it follows that

$$(\dot{Q}/\Delta T_m) = (\dot{Q}/\Delta T_{lm}) = \frac{633174}{5.8529} = 108181 \text{ W/K}$$

To estimate costs of these alternative designs, the *C*-value tables, in Appendix (C) are used [3]. Suppose there is a value C_1 at

$(\dot{Q}/\Delta T_m)_1$ and a value C_2 at $(\dot{Q}/\Delta T_m)_2$; the *C* value for the calculated $(\dot{Q}/\Delta T_m)$ is given by logarithmic interpolation and is as follows:

$$C = \exp\left\{\log_e C_1 + \frac{\log_e (C_1/C_2)\log_e[(\dot{Q}/\Delta T_m)/(\dot{Q}/\Delta T_m)_1]}{\log_e (\dot{Q}/\Delta T_m)_1/(\dot{Q}/\Delta T_m)_2}\right\}$$

For the double-pipe heat exchanger, the values C_1 = 1.4 at

$(\dot{Q}/\Delta T_m)_1$ = 100,000 and C_2 = 1.4 at $(\dot{Q}/\Delta T_m)_2$ = 1000,000 are read from the *C*-value tables, in Appendix (C) [3].

Thus for $(\dot{Q}/\Delta T_m)$ = 108181 the value of *C* is given by

$$C = \exp\left\{\log_e 1.4 + \frac{\log_e (1.4/1.4)\log_e[(108182)/(100000)]}{\log_e (100000)/(1000000)}\right\}$$

$$= 1.4 \text{ £/(W/K)}$$

Thus, the cost of the heat exchanger is:

Cost = $C \times (\dot{Q}/\Delta T_m)$ = 1.4 × 108181 = £151453

2.2 ABSORPTION CHILLER HEAT EXCHANGER

To calculate the initial cost of the absorption chiller heat exchanger, the same procedures of gas turbine heat exchanger will be applied.

$$\Delta T_{lm} = \frac{[(159.5 - 94.4) - (67.9 - 25)]}{\log_e [(159.5 - 94.4)/(67.9 - 25)]} = 53.23 \text{ K}$$

The heat load $\dot{Q}$ = 12,208,000 W
(from IPSEpro simulation software)

$$(\dot{Q}/\Delta T_m) = (\dot{Q}/\Delta T_{lm}) = \frac{12208000}{53.23} = 229341 \text{ W/K}$$

For the double-pipe heat exchanger, the values C_1 = 1.4 at

$(\dot{Q}/\Delta T_m)_1$ = 100,000 and C_2 = 1.4 at $(\dot{Q}/\Delta T_m)_2$ = 1000,000 are read from the *C*-value tables, in Appendix (C) [3].

Thus for $(\dot{Q}/\Delta T_m)$ = 229341 the value of *C* is given by

$$C = \exp\left\{\log_e 1.4 + \frac{\log_e (1.4/1.4)\log_e[(229341)/(100000)]}{\log_e (100000)/(1000000)}\right\}$$

$$= 1.4 \text{ £/(W/K)}$$

Thus, the cost of the heat exchanger is:

Cost = $C \times (\dot{Q}/\Delta T_m)$ = 1.4 × 229341 = £321078

The materials of heat exchangers were chosen in accordance with their function; the absorption chiller heat exchanger was chosen to be stainless steel E316 for its corrosion resistance ability, and the gas turbine heat exchanger was chosen to be stainless steel E304 in order to reduce its cost.

2.3 COMBINED CYCLES GAS TURBINE POWER PLANT

The power plant cost was estimated and obtained from the General Electricity Company of Libya (The General Electricity Company of Libya, [6]). The specific cost of the combined cycle gas turbine power plant with installation was £292.34/kW. That makes the purchase cost of the proposed power plant is £11,210,030.

2.4 SINGLE EFFECT WATER-LITHIUM BROMIDE ABSORPTION CHILLER

The absorption chiller cost was derived via a recent study by Boonnasa & Namprakai ([2]). The specific cost for the single-effect absorption chiller is £280 per refrigeration ton (RT). Consequently, the total purchase cost of the absorption chiller amounts to £385,000.

The cost of the power plant auxiliary equipments (motors, pumps, fans, filters, lubricants, valves, etc.) will be added as 5% of the total of all purchased equipment costs (Bejan et al, [1]).

Furthermore, based on (Bejan et al, [1]), the power plant purchased apparatus installation charge is 33%, piping cost is 35%, instrumentation and controls cost is 12% and electrical items and materials cost is 13% of the total purchased equipment costs respectively.

3. ANNUAL CASH OUTFLOW

The annual cash outflow comprises of fuel, operating and maintenance costs. It is being calculated as the annual function of power plant capacity factor (CF), which indicates the operating hours relative to the total available 8,760 hours per year. The fuel used is natural gas, with an estimated cost of £0.12/kg (Boonnasa & Namprakai, [2]). As a description of the power plant capacity factor, the operating and maintenance costs for each unit were carried out individually. For the combined cycle gas turbine power plant, the operating and maintenance cost is set at £3/MW·h according to a recent study by (Nisan & Benzarti, [5]) and (Methnani, [4]). Meanwhile, the operating and maintenance cost for the absorption chiller is £1.264/RT, as reported by (Boonnasa & Namprakai, [2]).

4. ANNUAL CASH INFLOW

The annual cash inflow consists of revenue generated from the sales of electrical power and the cooling effect produced by the absorption chiller. Based on pricing information from the General Electricity Company of Libya (The General Electricity Company of Libya, [6]) and a recent study by (Methnani, [4]), a value of £0.03/kW·h was adopted for both electric and cooling energy.

Additionally, another Microsoft Excel model (Figure 2) has been developed following the approach outlined by (Bejan et al, [1]) to calculate the final cost of capital investment, annual cash inflow, annual cash outflow, moreover to derive the findings of the four assessment criteria used. The model requires input data such as purchased equipment costs, interest rates, project lifespan and production and consumption metrics.

The assessment criteria incorporated in this particular model include techniques such as payback period, net present value, internal rate of return, and profitability index.

The payback period (PBP): It is defined as the length of time required to recover the cost of the initial total capital investment. It was calculated as:

$$\text{PBP} = \frac{\text{Total depreciable investment}}{\text{Total annual net cash inflow}}$$

Total depreciable investment = Total capital investment – Salvage value

Total capital investment = £24454913

The salvage value is defined as the scrap value of the power plant at the end of its economic life = £1900641

Total annual net cash inflow = £5052413/year

The payback period (PBP) = 4.5 years

There are two main problems with the payback period method:

- It ignores any benefits that occur after the payback period and, therefore, does not measure profitability.
- It ignores the time value of money. The idea that money available at the present time is worth more than the same amount in the future, due to its potential earning capacity.

Because of these reasons, other methods to evaluate the project like net present value (NPV), internal rate of return (IRR), profitability index (PI) are generally preferred.

Both IRR and NPV are widely used to decide which investments to undertake and which investments not to make.

Net Present Value (NPV): Net Present Value (NPV) is a way of comparing the value of money now with the value of money in the future. A pound today is worth more than a pound in the future, because inflation erodes the buying power of the future money, while money available today can be invested and grow. Then, a comparison can be made of that amount of money in the future with the amount of money needed to implement the project.

If the NPV is greater than the cost (i.e. positive) the project will be profitable and it should be accepted. However, if NPV is negative, the project should probably be rejected because the cost will also be negative.

$$\text{NPV} = \frac{\text{Sum of the total net cash inflow for each period}}{(1+\text{Interst rate})^{\text{period (year)}}} - \text{The initial total capital investment cost}$$

$$\text{NPV} = \sum_{y=0}^{t} \frac{CF_y}{(1+i)^y} - I_0$$

The result from the numerical iteration is NPV = £ 39225656

Internal Rate of Return (IRR): The return internal rate is basically the return rate on an investment. IRR is equivalent to the net present value calculation. The NPV calculation finds the net present value using a predefined discount rate. IRR finds the discount rate that makes the NPV equal to zero. The discount rate is the cost of borrowing or using money for investments. The decision to accept or reject the purchase depends on the whether the internal rate of return is higher than the discount rate. The decision standards for the projects is simple, accept the project if the IRR is higher than the discount rate or the cost of borrowing.

The internal rate of return (IRR) was being calculated as follows:

$$\text{NPV} = \sum_{y=0}^{t} \frac{CF_y}{(1+\text{IRR})^y} = 0$$

The result of IRR = 20.13 % (from the numerical iteration)

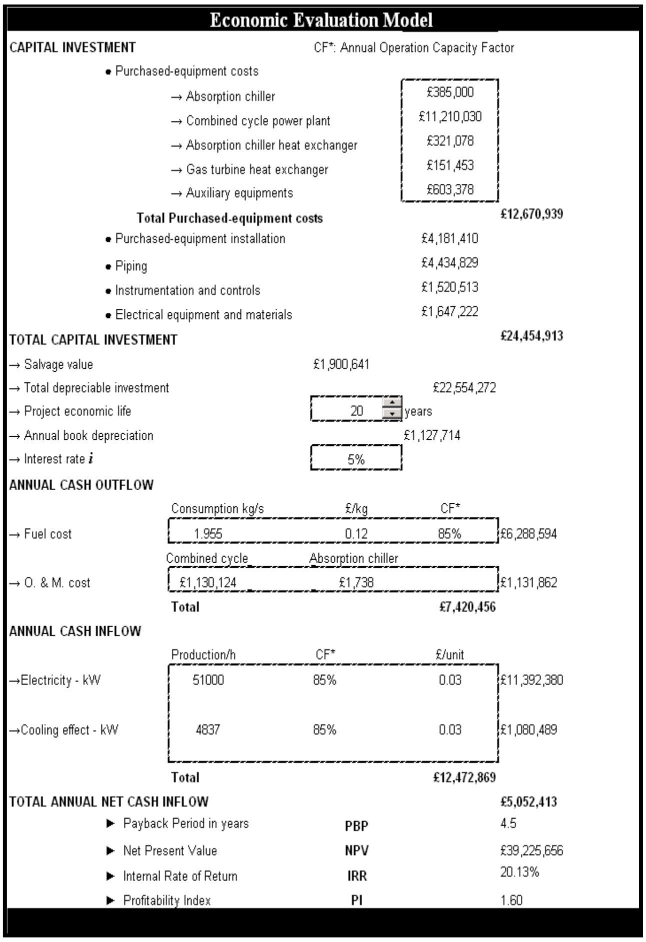
The Profitability Index (PI): The profitability index (benefit-cost ratio) is simply the present value of future cash flows divided by the initial capital investment. When the profitability index is greater than 1, the present value of cash flows must be greater than the initial capital investment. Therefore, the project must also have a positive net present value.

If the profitability index is less than 1, the project has to be rejected.

$$\text{The profitability index (PI)} = \frac{\text{Net Present Value}}{\text{Initial total capital investment cost}}$$

The profitability index (PI) was calculated as:

$$PI = \frac{NPV}{I_0} = \frac{£39225656}{£24454913} = 1.60$$



Economic Evaluation Model

CF*: Annual Operation Capacity Factor

CAPITAL INVESTMENT				
• Purchased-equipment costs				
→ Absorption chiller			£385,000	
→ Combined cycle power plant			£11,210,030	
→ Absorption chiller heat exchanger			£321,078	
→ Gas turbine heat exchanger			£151,453	
→ Auxiliary equipments			£603,378	
Total Purchased-equipment costs				£12,670,939
• Purchased-equipment installation			£4,181,410	
• Piping			£4,434,829	
• Instrumentation and controls			£1,520,513	
• Electrical equipment and materials			£1,647,222	
TOTAL CAPITAL INVESTMENT				£24,454,913
→ Salvage value	£1,900,641			
→ Total depreciable investment			£22,554,272	
→ Project economic life	20 years			
→ Annual book depreciation			£1,127,714	
→ Interest rate *i*	5%			
ANNUAL CASH OUTFLOW				
	Consumption kg/s	£/kg	CF*	
→ Fuel cost	1.955	0.12	85%	£6,288,594
	Combined cycle	Absorption chiller		
→ O. & M. cost	£1,130,124	£1,738		£1,131,862
	Total			£7,420,456
ANNUAL CASH INFLOW				
	Production/h	CF*	£/unit	
→Electricity - kW	51000	85%	0.03	£11,392,380
→Cooling effect - kW	4837	85%	0.03	£1,080,489
	Total			£12,472,869
TOTAL ANNUAL NET CASH INFLOW				£5,052,413
► Payback Period in years	PBP			4.5
► Net Present Value	NPV			£39,225,656
► Internal Rate of Return	IRR			20.13%
► Profitability Index	PI			1.60

Fig -2: MS Excel economic evaluation model screenshot

5. PARAMETRIC STUDY: RESULTS AND DISCUSSIONS

Several parametric studies have been conducted to assess the fluctuating variables impact, such as fuel costs and selling prices of product, on the project's economic performance. These studies also evaluate how variations in interest rates, capacity factors, and project lifespan influence the overall financial viability of the project.

The proposed power plant was operated under ISO conditions, utilizing the full load of the gas turbine with a project interest rate of 5%, a capacity factor of 85%, and a project lifespan of 20 years. To evaluate the impact of fuel costs on the power plant's economic performance, fuel prices were varied while keeping operating and maintenance costs constant.

The results presented in Figure (3) indicate that the fuel price becomes non-viable when it exceeds £0.143/kg, at which point the profitability index falls below 1. The payback period reaches 6 years when the fuel price is set at £0.143/kg. A decrease in fuel prices leads to a reduction in annual cash outflow, resulting in an improved profitability index and a shorter payback period.

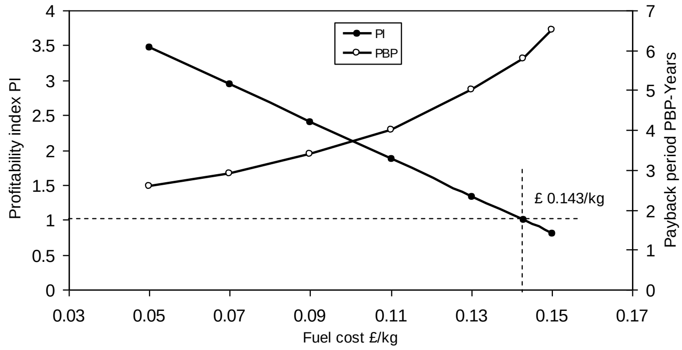


Fig -3: Fuel cost versus PI and PBP

In Figure (4), the net present value decreased as the fuel cost increased. The internal rate of return declines with the increase in fuel cost to reach 14.77% at a fuel price of £0.143/kg.

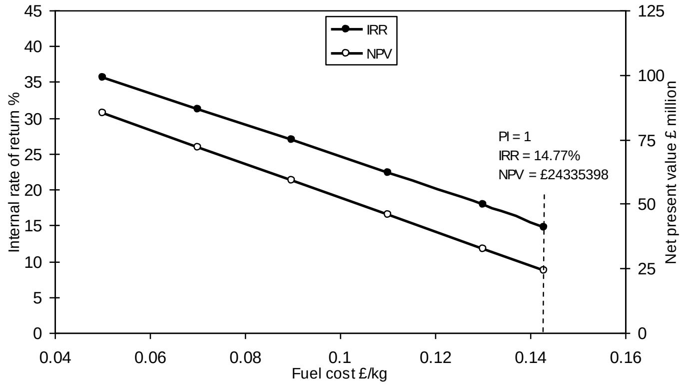


Fig -4: Fuel cost versus IRR and NPV

The variation in interest rate significantly affects the net present value, as illustrated in Figure (5). The analysis indicates that the project becomes economically unviable and should be rejected if the interest rate exceeds 20.13%. At this threshold, the net present value falls below zero.

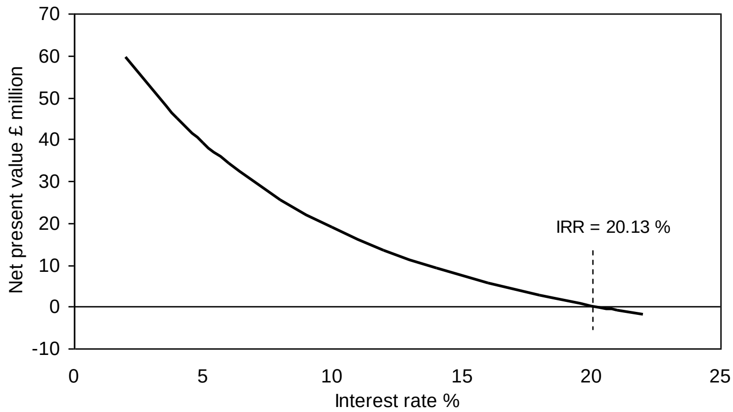


Fig -5: Interest rate versus net present value (NPV)

The project lifespan was assessed using consistent economic evaluation criteria, namely net present value (NPV) and profitability index (PI). Both the NPV and PI showed an upward trend with an extended project life. As illustrated in Figure (6), at a 20 years lifespan, the net present value amounted to £39,225,656, and the profitability index stood at 1.60.

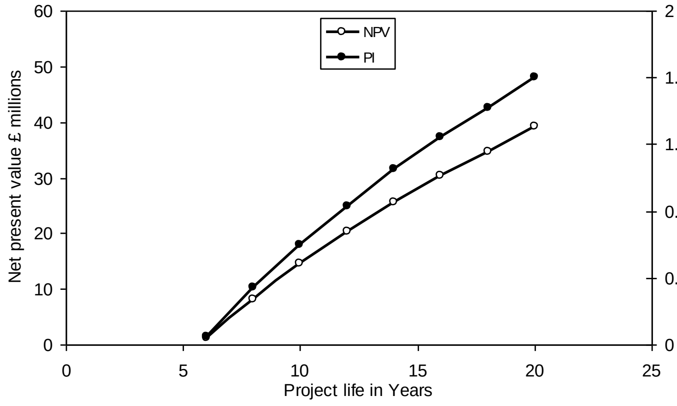


Fig -6: Project lifetime versus NPV and PI

Furthermore, the payback period usually increases with the increase in the operating and maintenance cost, hence that reduces the net present value Figure (7).

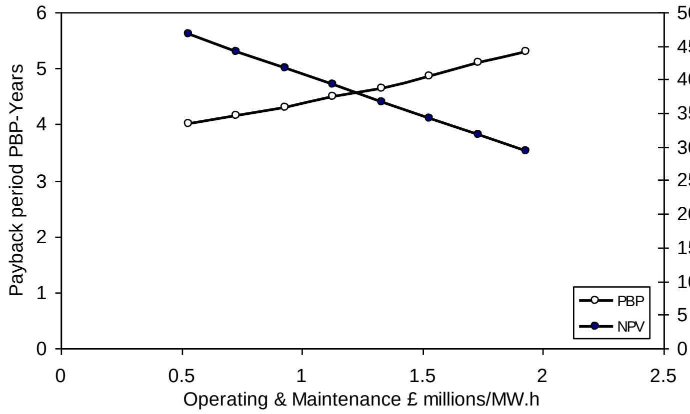


Fig -7: Operating and maintenance versus NPV and PBP

In this study, the capacity factor was set at 85%, reflecting typical values for power plants (Bejan et al., [1]). However, other studies have suggested higher capacity factors, prompting a parametric study to explore the effects of increasing the capacity factor on key economic evaluation standards.

Using a built MS Excel model, the capacity factor was varied from 60% to 100% in 5% increments, while maintaining the gas turbine at full load. As the capacity factor increased, fuel consumption also rose, leading to higher production rates with only a nominal increase in operating and maintenance (O&M) costs. This improvement positively influenced both the net present value and the internal rate of return.

The profitability index increased alongside the capacity factor, while the payback period was reduced by four months for every 5% rise in the capacity factor, as depicted in Figure (8).

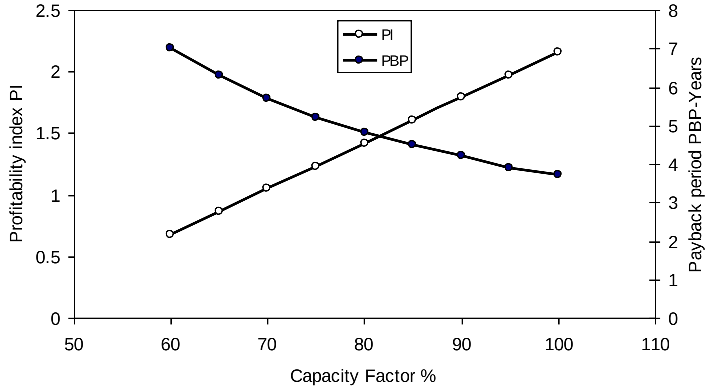


Fig -8: Capacity factor versus PI and PBP

Using the built MS Excel model (Figure 2), a variation in energy selling prices was analyzed, ranging from £0.022/kW.h to £0.09/kW.h in increments of £0.01/kW.h, while the gas turbine operated at full load. The results showed that increasing the energy selling price above £0.04/kW.h only reduced the payback period by 4 months, as illustrated in Figure (9).

In contrast, the other economic evaluation criteria i.e net present value (NPV), profitability index (PI), and internal rate of return (IRR) showed a direct proportionality with the rise in energy selling prices. Furthermore, to achieve a payback period of less than 4.5 years, the energy selling price must be no lower than £0.028/kW.h to avoid any decrease in the profitability index less than 1.

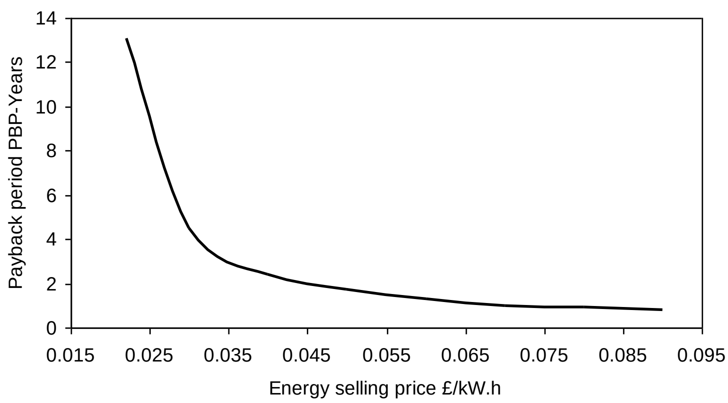


Fig -9: Energy selling prices versus PBP

6. CONCLUSION AND REMARKS

This research conducted an economic evaluation study that utilized four key criteria: payback period (PBP), internal rate of return (IRR), profitability index (PI) and net present value (NPV) to assess the economic viability of the proposed power plant.

The initial costs for the heat exchangers, single-effect absorption chiller and combined cycle gas turbine power plant were determined using a custom-built economic MS Excel model, which also defined all other capital costs. Annual cash inflows and outflows were calculated through this model to derive the selected evaluation criteria.

A parametric study was then performed to investigate the acceptability of the power plant's performance, focusing on various economic variables such as fuel price, interest rate, project lifetime, capacity factor, and energy selling prices.

The findings indicated that the power plant is economically viable and profitable, with a payback period not exceeding 4.5 years, a profitability index of up to 1.60, an internal rate of return of 20.13%, and a net present value reaching £39 million. It was also noted that fuel costs had the most significant impact on the economic performance of the power plant, while interest rates above 20.13% were deemed economically unacceptable. Additionally, extending the project lifetime showed considerable benefits for the power plant within the first twenty years. Lastly, energy selling prices were identified as critical to economic performance, with a minimum threshold of £0.028/kW.h established to maintain profitability.

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