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Comparative Economic Analysis of Simple and Modified Cycle Gas Turbine Power Plants

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Abstract— This work presents a comparative economic analysis of a simple and a modified cycle gas turbine power plants. The basic engine used for this work is a PG 6581 B gas turbine engine which is operated by a company in the Niger Delta area of Nigeria. The modified cycle was developed from the simple cycle engine with an intercooler between two compressors, a reheater between two turbines and a regenerator which heats up the second compressor exit gases with the second turbine exit gases. The net present value and the levelized cost of electricity methods were applied to investigate the economic viability of the two plants. The modified cycle was analyzed at regenerative effectiveness values between 80% and 100%. The fuel flow rate in the simple cycle plant was obtained from the field as 2.13 kg/s while the total fuel flow rate in the modified cycle ranged from 2.41kg/s to 2.08kg/s. The power output in the simple cycle plant was 35.52MW while that in the modified cycle plant ranged between 58.28MW and 58.03MW. The thermal efficiency of the simple cycle plant was 34.38% which is much lower than that of the simple cycle plant that stood at 51.16% to 58.94%. The net present value for 20 years period of engine operation considering 11% interest rate was $2.78 Million for the simple cycle plant and in the range $42.65 Million to $63.93 Million for the modified cycle plant. The levelized cost of electricity for engine life cycle of 20 years was 18.48N/kW-hr for the simple cycle plant and in the range 15.48N/kW-hr to 14.29N /kW-hr for the modified cycle plant. Both the engineering and the economic results favours the operation of the modified cycle plant.

Index Terms—Gas Turbine, Levelized cost of electricity, Simple cycle, Modified cycle, Regenerative effectiveness, Net present value, Levelized cost of electricity.

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1 INTRODUCTION

The power sector in Nigeria has a lot of gas turbines operating mainly on the simple cycle basis. Aeroderivative gas turbine units have also been used; an example is the Trans-Amadi power station, Port Harcourt. The simple cycle gas turbine engine is generally used for power production but one major setback associated with the operation of the gas turbine engine is the cost of the fuel [1] , [2]. Efforts are thus being made to modify the simple cycle gas turbine engine such that the resulting cycle will produce the same power for a given pressure ratio but consumes less fuel. The regenerative cycle [3] , [4] is a typical example of a modified cycle where the fuel consumption is lower depending on the regenerative effectiveness of the regenerator. For a gas turbine engine with high pressure ratio, it is appropriate to employ more than one compressor in the compression process with intercooling and employ more than one turbine in the expansion process with reheating. The usage of two compressors and two turbines is common and the gases at the exit of the second compressor are heated up with the gases at the exit of the second turbine and the resulting cycle is referred to as gas turbine cycle with intercooling, regeneration and reheat [3] , [4]. The essence of high pressure ratio is to have high thermal efficiency [5] , [6], meaning burning less fuel to produce given amount of power.

The comparative exergo-environmental analysis of the simple and the regenerative cycle gas turbine has been studied [7] where it was observed that the environment is safer with the operation of the regenerative cycle plant. The thermodynamics as well as economic performance analysis of different configurations of gas turbine engines have also been studied [8], [9], [10], [11], 12]. Some works on gas turbine performance analysis are based on the exergoeconomic approach where the cost of flow streams are assessed from the second law considerations [13] , [14]. It is necessary to compare the economic implications of operating different engine configurations for power production. In this work, economic analysis of the simple cycle gas turbine engine and the modified cycle gas turbine engine with intercooling, regeneration and reheating were carried out using a frame 6 gas turbine engine (Model: PG 6581 B) operated by a company in the Niger Delta area of Nigeria. The performance parameters of this gas turbine engine were investigated in [7], therefore, in the present work; some of those results were used in developing the modified cycle plant. The net present value and the levelized cost of electricity methods were used for the economic analysis.

2 MATERIALS AND METHODS

Different costs involved in gas turbine operation were estimated. These include the initial cost of setting up the plant and operation and maintenance (O&M) cost. More effective cost analysis requires separating the cost of fuel from the O&M cost and that approach was adopted here. The revenue comes from the sale of electricity and it is estimated for both plants from the power output and the price of electricity. The net power outputs from both plants were first estimated (although, that from the simple cycle plant was obtained from the field). The modified cycle was derived from the simple cycle and the engine performance parameters such as isentropic efficiencies of the compressor and the turbine obtained in the simple cycle are transferred to the modified cycle in order to create proper platform for comparison of performance results. The fuel flow rates of both plants were obtained for the economic analysis

2.1 Performance analysis and estimation of simple cycle maximum temperature

Details of the performance analysis procedure of the simple cycle plant can be found in [7] and [15]. Here, we have to obtain the turbine entry temperature and the different components efficiencies. Figure 1 shows the T-s diagram of the simple cycle plant, where process 1-2i is the isentropic compression, process 1-2a is the actual compression, process 3-4i is isentropic expansion and process 3-4a is the actual expansion.

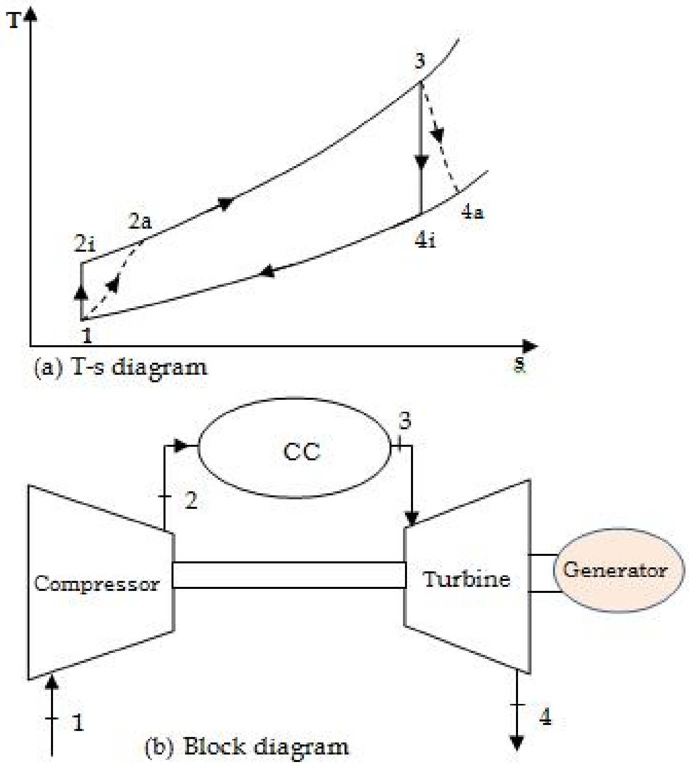

Fig. 1. Temperature- entropy (T-s) and block diagrams of a real gas turbine engine

The net power output and the fuel flow rate for the simple cycle were obtained from the field as 35.52 MW and 2.13 kg/s respectively. The pressure ratio of the cycle was 12.7, which is appropriate for regeneration while the exhaust gas temperature was 812.77K. The isentropic efficiency of the compressor, the isentropic efficiency of the turbine, the combustion efficiency, combustion pressure loss and exhaust pressure loss were estimated using in-house software [7], [15] as shown in Table 1 and these data were used in the modified cycle.

TABLE 1
BASIC FEATURES OF THE SIMPLE CYCLE ENGINE [7]

S/N	Parameter	Symbol	Unit	Value
1	Isentropic Efficiency of the Compressor	η_{ci}	%	81.11
2	Isentropic Efficiency of the Turbine	η_{ti}	%	87.44
3	Combustion Efficiency	η_{cc}	%	97.00
4	Pressure Loss in Combustion Process	ΔP_{CC}	%	3.44
5	Pressure Loss in the Exhaust	ΔP_{EX}	%	5.00

The next parameter to be transferred to the modified cycle is the highest temperature in the simple cycle, T3 given by Equation (1),

$$T_3 = \frac{\dot{m}_a c_{p,a} T_{2a} + \dot{m}_f LCV_f \eta_{cc}}{(\dot{m}_a + \dot{m}_f) c_{p,g}} \quad (1)$$

where $\dot{m}_a$, $\dot{m}_f$, $c_{p,a}$, $c_{p,g}$, LCV_f and η_{cc} are respectively the air flow rate in (kg/s), the mass flow rate of the fuel, the specific heat capacity of air, the specific heat capacity of the flue gases, the lower calorific value of the fuel and the combustion efficiency.

The net power output W_{net} is,

$$W_{net} = \dot{W}_t - \dot{W}_c \quad (2)$$

where $\dot{W}_t$ is the turbine power output and $\dot{W}_c$ is the power consumed by the compressor. The power consumed by the compressor and the turbine power output are given by Equations (3) and (4) respectively,

$$\dot{W}_c = \dot{m}_a c_{p,a} (T_{2a} - T_1) \quad (3)$$

$$\dot{W}_t = \dot{m}_{a,f}\, c_{p,g} (T_3 - T_{4a}) \quad (4)$$

where $\dot{m}_{a,f} = \dot{m}_a + \dot{m}_f$. The temperatures T_{2a} and T_{4a} are given by Equations (5) and (6) respectively,

$$T_{2a} = T_1 + \frac{(T_{2i} - T_1)}{\eta_{c,i}} \quad (5)$$

$$T_{4a} = T_3 - \eta_{T,i} (T_3 - T_{4i}) \quad (6)$$

where $\eta_{C,i}$ is the isentropic efficiency of the compression process and $\eta_{T,i}$ is the isentropic efficiency of the expansion process. T2i and T4i are given by Equations (7) and (8) respectively,

$$T_{2i} = T_1 (r_p)^{\frac{\gamma - 1}{\gamma}} \quad (7)$$

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$$T_{4i} = T_3 (r_p)^{\frac{1 - \gamma_g}{\gamma_g}} \quad (8)$$

where r_p is the pressure ratio across the turbine and γ is the ratio of specific heat capacities.

2.2 Engineering Performance Analysis of the Modified Cycle

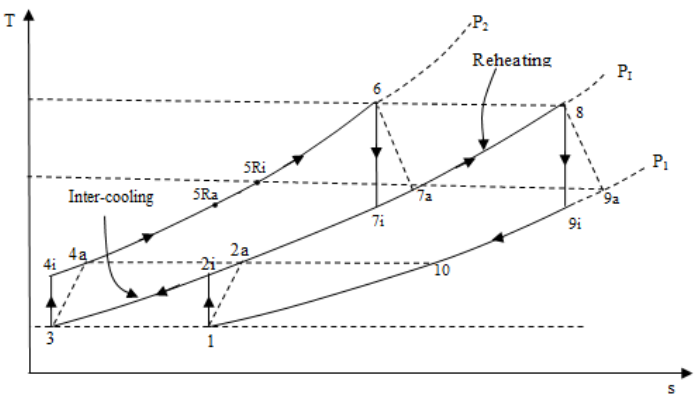

Fig.2. Temperature- entropy (T-s) diagram of the modified cycle

The T-s diagram of the modified cycle is shown in Figure 2. Process 1-2i is the ideal compression process while process 1-2a is the actual compression process in the first compressor. Process 2a-3 is the intercooling process. The ideal and actual compression processes in the second compressor are 3-4i and 3-4a respectively. The working fluid enters the regenerator from 4a and comes out as 5Ra for the real regenerator and 5Ri for the ideal regenerator. The pressure losses in the intercooler and regenerator are neglected in this work but those of the combustion and reheat processes are taken as the combustion pressure loss in the simple cycle. Process 5Ra-6 is the combustion process where fuel is added to the working fluid. Processes 6-7a is the actual expansion process in the first turbine while process 7a-8 is the reheating process. Process 8-9a is the actual expansion process in the second turbine. The net power output from the plant and the fuel flow rates in the combustion and reheat processes were estimated.

The net power output of the modified cycle $\dot{W}_{net,M}$ is,

$$\dot{W}_{net,M} = \dot{W}_{T,M} - \dot{W}_{C,M} \qquad (9)$$

where $\dot{W}_{T,M}$ is the turbine power output from the two turbines and $\dot{W}_{C,M}$ is the power consumed by the two compressors. The power consumed by the two compressors (processes 1-2a and 3-4a) are the same and given as,

$$\dot{W}_{C,M} = \frac{2c_{p,a}\dot{m}_a T_1\left(r_p^{\frac{\gamma-1}{2\gamma}}-1\right)}{\eta_{c,i}} \qquad (10)$$

The power produced by the two turbines (processes 6-7a and 8-9a) are the same in the ideal case but is given here as shown in Equation (11) because of the different mass flow rates through the turbines,

$$\dot{W}_{T,M} = \begin{Bmatrix} \dot{m}_{a+f}c_{p,g}\left(T_6 - T_{7i}\right) \\ +\left(\dot{m}_{a+f}+\dot{m}_{f,r}\right)c_{p,g}\left(T_8 - T_{9i}\right) \end{Bmatrix} \times \eta_{T,i} \qquad (11)$$

where $\dot{m}_{f,r}$ is the additional fuel burnt in the reheat process. T8=T6 and T9i=T7i, thus, Equation (11) can be re-written as in Equation (12) exploiting the intermediate pressure ratio,

$$\dot{W}_{T,M} = \left\{c_{p,g}T_6\left(1-r_p^{\frac{1-\gamma}{2\gamma}}\right)\left(2\dot{m}_{a+f}+\dot{m}_{f,r}\right)\right\}\times\eta_{T,i} \qquad (12)$$

where $\dot{m}_{a+f} = \dot{m}_a + \dot{m}_{f'}$; $\dot{m}_{f'}$ is the fuel flow rate in the combustion chamber (CC). Also,

$$\frac{T_6}{T_{7i}} = \frac{T_8}{T_{9i}} = r_p^{\frac{1-\gamma}{2\gamma}} \text{ and } \frac{P_2}{P_I} = \frac{P_I}{P_1} = \left(\frac{P_2}{P_1}\right)^{\frac{1}{2}} = \left(r_p\right)^{\frac{1}{2}}$$

Pressure drops are accounted for in the computations. The fuel flow rate in the CC depends on the effectiveness of the regenerator and it is given as,

$$\dot{m}_{f'} = \frac{\dot{m}_a c_{p,a}\left(T_6 - T_{5Ra}\right)}{\eta_{cc}LCV_f} = \frac{\dot{m}_a c_{p,a}\left(T_6 - T_{4a} - \varepsilon\left[T_{9a} - T_{4a}\right]\right)}{\eta_{cc}LCV_f} \qquad (13)$$

where ε is the effectiveness of the regenerator, taken in the range of 80% to 100% in this work. The actual temperatures at the exits of the first and second compressors are the same and it is given as,

$$T_{4a} = T_{2a} = T_1 + \frac{\left(T_{2i} - T_1\right)}{\eta_{C,i}} \qquad (14)$$

$$T_{2i} = T_{4i} = T_1\left(r_p\right)^{\frac{\gamma-1}{2\gamma}} \qquad (15)$$

The actual temperature at the exit of the second turbine is the same as that at the exit of the first turbine as given in Equation (16),

$$T_{9a} = T_{7a} = T_6 - \eta_{T,i}\left(T_6 - T_{7i}\right) \qquad (16)$$

The additional fuel burnt in the reheat process is obtained by carrying out energy balance in the reheater as,

$$\dot{m}_{a+f}c_{p,g}T_7 + \dot{m}_{f,r}LCV_f = \left(\dot{m}_{a+f} + \dot{m}_{f,r}\right)c_{p,g}T_8 \qquad (17)$$

Rearranging, noting that T_8=T_6, the additional fuel burnt in the reheater is,

$$\dot{m}_{f,r} = \frac{\dot{m}_{a+f}c_{p,g}\left(T_6 - T_{7a}\right)}{LCV_f - c_{p,g}T_8} \qquad (18)$$

The total fuel flow rate in the modified cycle is thus,

$$\dot{m}_{f,T} = \dot{m}_{f'} + \dot{m}_{f,r} \qquad (19)$$

2.3 Economic Analysis of the Plants

The costs, the revenues and the methods of economic analysis were considered here. The basic costs in both plants are the installation cost (IC), O&M cost (CO&M) and fuel cost (CF). Emission cost can be considered in some cases. The cost of installing a gas turbine power plant depends on the amount of power produced and it is expressed in US dollars as US $/kW. The installation and O&M cost values used in this work were obtained from [16], [17]. The cost of setting up the modified cycle plant was estimated from the power output obtained for the plant. The fuel cost is calculated by multiplying the fuel flow rate by the cost of fuel in the market which is about $10 per thousand cubic feet which is expressed in per kilogram basis as in [18]. The total annual operating cost AC is thus,

$$AC = C_{O\&M} + C_F \qquad (20)$$

If the installation cost is annualized over the life cycle of the plant, the annual operating cost will be,

$$AC = A_{IC} + C_{O\&M} + C_F \qquad (21)$$

where A_{IC} is the annualized installation cost. The time value of money is accounted for in annualizing the installation cost.

The annual revenue is derived from electricity sales, and the price is expressed in Naira per kilo-Watt hour (N/kWhr). The price of electricity used in this work was obtained from [19]. The two economic tools employed in this this work are the net present value (NPV) method and the levelized cost of electricity method. The NPV is obtained as,

$$NPV = \sum_{i=1}^{n} \frac{NACF_i}{(1+r)^i} - IC \qquad (22)$$

where $NACF_i$ is the net annual cash flow (the difference between the annual income and the annual cost of plant operation) and r is the interest rate. A high value of NPV portrays a viable project. The levelized cost of electricity (LCOE) is expressed as the ratio of the total life cycle cost (TLCC) to the total life cycle energy production (TLEP) [20]. This is given as,

$$LCOE = \frac{TLCC}{TLEP} \qquad (23)$$

For the gas turbine plant operation, twenty (20) yaers life cycle was assumed in this work and the total life cycle cost and life time energy production are given as shown in Equations (24) and (25) respectively,

$$TLCC = \sum_{i=1}^{n} \left(A_{IC,i} + C_{O\&M,i} + C_{F,i} \right) \qquad (24)$$

$$TLEP = \sum_{i=1}^{n} \left(W_{net,i} \times 1000 \times y_i \right) \qquad (25)$$

where $W_{net,i}$ is the net power produced (in MW) and y is the number of hours the engine is operated per annum. Here, the engine is assumed to be available 90% of the time which amounts to 7884hrs per year. The total life cycle cost was brought to the present value in the analysis. The unit of LCOE is N/kW-hr or $/kW-hr.

3. RESULTS AND DISCUSSION

The engineering performance parameters including the fuel flow rate and the thermal efficiency of both the simple and modified cycle power plants are shown in Table 2. The fuel flow rate of the simple cycle plant obtained from the field was 2.13 kg. The modified cycle plant has fuel flow in CC as well as the reheater. Total fuel flow rate decreases from 2.4115kg/s at a regenerative effectiveness of 80% to 2.0833kg/s at 100% regenerative effectiveness which is lower than that of the simple cycle plant.

TABLE 2
ENGINEERING PERFORMANCE PARAMETERS OF THE SIMPLE AND MODIFIED CYCLE PLANTS

Parameter	Cycle Type					
	Simple Cycle	Modified Cycle				
		Regenerative Effectiveness (-)				
		0.8	0.85	0.9	0.95	1
Fuel Flow Rate in CC (kg/s)	2.13	1.3546	1.2732	1.1918	1.1104	1.0290
Fuel Flow in the Reheater (kg/s)	_	1.0568	1.0562	1.0556	1.0550	1.0543
Total Fuel Flow Rate (kg/s)	_	2.4115	2.3294	2.2474	2.1654	2.0833
Net Work Output (MW)	35.52	58.28	58.21	58.15	58.09	58.03
Heat Input (MW)	103.31	113.90	110.04	106.18	102.32	98.46
Thermal Efficiency (%)	34.38	51.16	52.90	54.77	56.78	58.94

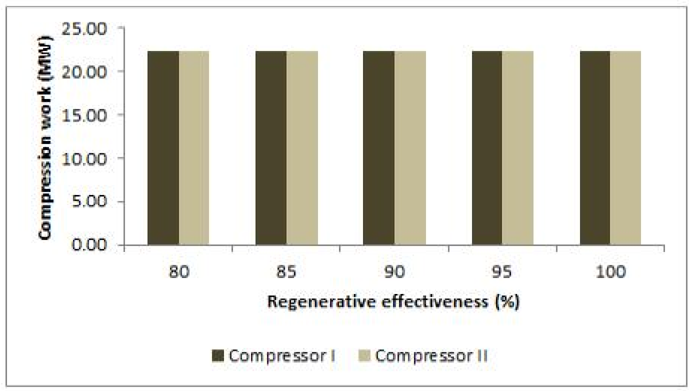

Fig. 3. Compressor work consumed from the two compressors

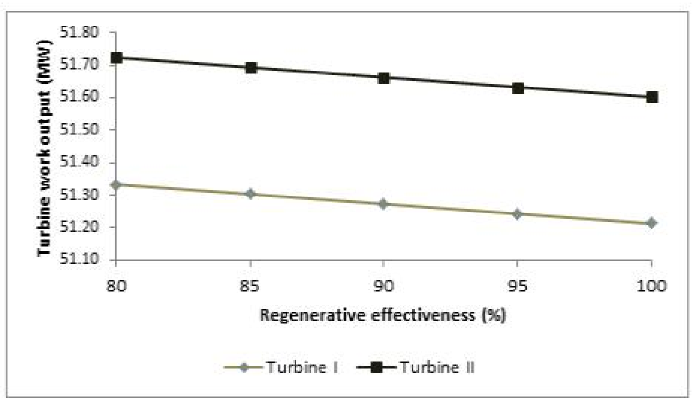

Fig. 4. Turbine work outputs from the two turbines

The net power output of the modified cycle plant ranges from 58.28MW at 80% regenerative effectiveness to 58.03MW at 100% regenerative effectiveness. The net power output in the modified cycle decreases gradually with the regenerative effectiveness because of the decrease in the fuel flow rate with the regenerative effectiveness and the turbines are meant to expand to same atmospheric condition. The net power output from the simple cycle plant is much lower than that from the modified cycle at all values of the regenerative effectiveness.

The net power output comes from the two compressors and the two turbines. The power consumed by the two compressors is the same at all values of regenerative effectiveness but the power output from the two turbines decreases with regenerative effectiveness as shown in Figures 2 and 3 respectively. The compressor works are the same because the working fluid at the exit of the first compressor is intercooled to same ambient temperature level before being admitted into the second compressor and regeneration does not affect the compressors. In the turbines, the power output of the second turbine is greater than that of the first turbine at all values of the regenerative effectiveness because of the additional fuel burnt in the reheater which adds to the total mass flow rate of the working fluid in the second turbine.

TABLE 3

CASH FLOW AND NET PRESENT VALUE OF THE SIMPLE CYCLE PLANT

Parameter	YEAR										Total	NPV
	1	3	5	7	9	11	13	15	17	20		
Installed Cost (M$)	-22.38	0	0	0	0	0	0	0	0	0	-22.38	
NACF (M$)	3.16	3.16	3.16	3.16	3.16	3.16	3.16	3.16	3.16	3.16	63.18	
Discount factor at 11%	0.90	0.73	0.59	0.48	0.39	0.32	0.26	0.21	0.17	0.12		
Discounted NACF (M$)	2.85	2.31	1.87	1.52	1.23	1.00	0.81	0.66	0.54	0.39	25.15	2.78
Cumulative NACF	2.85	7.72	11.67	14.88	17.49	19.61	21.32	22.71	23.85	25.15		

Table 3 presents the cash flow and the NPV of the simple cycle plant. The cash flow is shown for a selected number of years. The NPV is 2.78 million US Dollars which is lower than the lowest value obtained in the modified cycle at 80% regenerative effectiveness as in Table 4. The cash flow in the modified cycle plant is also shown for selected years. The NPV in the modified cycle increases with the regenerative effectiveness. This is because the fuel flow rate decreases with the regenerative effectiveness and the major cost of the plant operation comes from the fuel. In terms of the NPV, the modified cycle plant is far more profitable to operate compared to the simple cycle plant.

The levelized cost of electricity which represents the cost of producing one kW-hr of electricity is shown for the two plants in Table 5. The levelized cost of electricity for the simple cycle plant is $0.0513 which is equivalent to N18.48 using an exchange rate of N360 to a dollar. This value is nearly twice the average price of electricity as in [20] used in this work. Considering the cost of transmission and distribution, the final electricity price to the customers twice this value will be high enough for engine operators to be in business. The levelized cost of electricity of the modified cycle plant ranged from 0.0430$/kW-hr to 0.0397$/kW-hr (15.48N/kW-hr to 14.29N /kW-hr). The value decreases with increase in the regenerative effectiveness because the amount spent on fuel reduces with the regenerative effectiveness. The levelized costs of electricity values obtained from the modified cycle plant are much lower than that for the simple cycle plant. This means lower cost of electricity and hence more profit for operating the modified cycle plant as against the simple cycle plant.

TABLE 4

CASH FLOW AND NET PRESENT VALUE OF THE MODIFIED CYCLE PLANT

Parameter	YEAR											Total	NPV
	1	3	5	7	9	11	12	13	15	17	20		
Installed Cost (M$)	-44.75	0	0	0	0	0	0	0	0	0	0	-44.75	
NACF (M$)													
At 80% Reg Eff	10.98	10.98	10.98	10.98	10.98	10.98	10.98	10.98	10.98	10.98	10.98	219.52	
At 85% Reg Eff	11.64	11.64	11.64	11.64	11.64	11.64	11.64	11.64	11.64	11.64	11.64	232.88	
At 90% Reg Eff	12.31	12.31	12.31	12.31	12.31	12.31	12.31	12.31	12.31	12.31	12.31	246.24	
At 95% Reg Eff	12.98	12.98	12.98	12.98	12.98	12.98	12.98	12.98	12.98	12.98	12.98	259.60	
At 100 % Reg Eff	13.65	13.65	13.65	13.65	13.65	13.65	13.65	13.65	13.65	13.65	13.65	272.96	
DF at 11%	0.90	0.73	0.59	0.48	0.39	0.32	0.29	0.26	0.21	0.17	0.12		
Discounted NACF (M$)													
At 80% Reg Eff	9.89	8.03	6.51	5.29	4.29	3.48	3.14	2.83	2.29	1.86	1.36	87.40	42.65
At 85% Reg Eff	10.49	8.51	6.91	5.61	4.55	3.69	3.33	3.00	2.43	1.98	1.44	92.72	47.97
At 90% Reg Eff	11.09	9.00	7.31	5.93	4.81	3.91	3.52	3.17	2.57	2.09	1.53	98.04	53.29
At 95% Reg Eff	11.69	9.49	7.70	6.25	5.07	4.12	3.71	3.34	2.71	2.20	1.61	103.36	58.61
At 100 % Reg Eff	12.30	9.98	8.10	6.57	5.34	4.33	3.90	3.51	2.85	2.32	1.69	108.68	63.93

TABLE 5

LEVELIZED COST OF ELECTRICITY FROM BOTH THE SIMPLE CYCLE AND THE MODIFIED CYCLE PLANTS

Parameter	Cycle Type					
	Simple Cycle	Modified Cycle				
		Regenerative Effectiveness (-)				
		0.8	0.85	0.9	0.95	1
Total Energy Produced (kW-hr)	5600793600	9188848060	9179327181	9169806302	9160285422	9150764543
Total Life Cycle Cost (M $)	191.66	263.43	258.11	252.79	247.47	242.15
Levelized Cost of Electricity ($/kW-hr)	0.051329092	0.0430	0.0422	0.0414	0.0405	0.0397

4. CONCLUSION

Comparative economic analysis of a simple and a modified cycle gas turbine power plants was carried out. The modified cycle has an intercooler, reheater and a regenerator. The net present value and the levelized cost of electricity methods were applied to investigate the economic viability of the two plants where the modified cycle was analyzed at regenerative effectiveness values between 80% and 100%. It was observed that the net present value of the simple cycle plant was far less than those of the modified cycle plant whose values increased as the regenerative effectiveness of the regenerator increases. The cost of producing a unit amount of electricity was lower in the modified cycle and consequently decreases as the regenerative effectiveness increases. Thus, it is more profitable to operate the modified cycle plant as against the simple cycle plant.

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