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Comparative Performance Assessment of Different Gas Turbine Configurations: A Study of a Local Power Station in Nigeria

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Research Article

Abstract

A comparative assessment of gas turbine options for power generation was carried out in this paper. The existing Omotosho power station in Nigeria which is based on the simple cycle and its retrofitted modified cycles were used for the investigation. The thermal efficiency, specific fuel consumption and power output are important performance criteria used in comparing cycles. DWSIM, a multiplatform open-cape software was used in carrying out the simulations for the simple circle and the integrated intercooler, reheater and regenerative cycles. The percentage changes in performance of these cycles over the simple cycle was evaluated and found to exhibit better performances in terms of thermal efficiency, specific fuel consumption and power output than the conventional simple cycle achieving up to 68% increment in some cases.

Keywords

Gas turbine; Simple Cycle; Intercooler; Reheater; Regenerator Efficiency

Article History

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1. Introduction

Gas turbines are considered mainly for power generation and propulsion systems. They have long displaced internal combustion engines in electricity generation and aircraft propulsion applications which unequivocally, can be attributed to their good Power to weight ratio and been lighter and smaller than similar internal combustion engines (Agriculture & Slide, 1991; Zohuri, *et al.*, 2018).

A typical gas turbine unit comprises of a compressor, a combustion chamber, a gas turbine and an alternator and a sta. The working fluid in a typical gas turbine power plant is air. The intake air is compressed in the compressor, then passed to the combustion chamber where the gases are burnt, thereby, raising its temperature. With the burning of fuel in the combustion chamber, the compressed air is heated up to produce high temperature flue gas. The gas turbine, as an expander, receives the hot and high pressure gases from the combustion chamber, expands it and by so doing generates the mechanical work. In turn, the gas turbine powers the alternator which converts the mechanical energy into electrical energy (Aj, 2016). Electricity is an important indices in the economic, social and technological wellbeing of every nation. The electricity demand in Nigeria is far higher than the current supply. The country is greatly hindered by its electricity problems, which is slowing down its development despite the country's vast natural resources (Sambo, *et al.*, 2010). An estimate of 21 percent of the world's electricity production is based on natural gas. With a maximum crude oil production capacity of 1.9 million barrels per day, Gas power plant has outstanding prospects in Nigeria. The maximum installed capacity of this type of power plant in Nigeria is Delta Power Station with 900 MW (Aj, 2016). According to (Emodi & Yusuf, 2015), 20 out of the 30 existing operational power stations in Nigeria are gas turbine plants.

A peak efficiency of up to 35% is achieved when the gas turbines is running on the simple Brayton cycle (Oyedepo *et al*., 2015). To improve this efficiency, the simple cycle can be modified by incorporating performance enhancers such as intercoolers, reheaters and regenerators. These modification have been known to increases gas turbine efficiency up to 45% .The cut down on fuel and the improved efficiencies justifies the added complexity this modifications would bring to design and other operational cost.

A number of authors have studied the effect of modifications on gas turbine performances. For instance, Oyedepo (Oyedepo *et al*., 2014). studied how the efficiency and electric power generation of gas turbines is affected by the ambient conditions, he compared their effect in gas turbines to other types of conventional power plants, the study showed that gas turbines were the most affected by fluctuations in air ambient temperature.

The study carried out by Ejanavi (Ejenavi, 2018), it was discovered that the overall efficiency of the gas turbine cycle depends primarily on the pressure ratio of the compressor

Rahman (Rahman *et al*., 2010) emphasizes that gas that operate in simple cycles have low efficiencies due to the high temperature exhaust gas which would have been lost to the atmostphere. By incorporating a counter-flow heat exchanger in their model, the thermal efficiency of the gas turbine increases while the specific fuel consumption decreases.

From a parametric study carried out by Omar (Omar et al., 2017), results showed that the air inlet temperature and compression ratio has a major effect on the thermal efficiency of a simple thermodynamic and regenerative gas turbine cycles. The inclusion of a recuperator in a simple gas turbine cycle, resulted in the increase of thermal efficiency of the cycle with a reduction in fuel consumption of the gas turbines. Increase in the compression ratio also resulted in increased thermal efficiency of both the simple and regenerative gas turbine cycle.

Staudt (Staudt, 1989) found that for a simple thermodynamic gas cycle for gas turbine engines, incorporation of non-conventional components as intercoolers and recuperators not only increases the operating efficiency, it significantly increases the power output generated by the turbine engines with a reduction in fuel consumption by the turbine engines. The application of ICR (Intercooler-Recuperator unit) to gas turbine engines is an important method for improving the overall operating efficiency and power output of the gas turbine engines.

In the comparative assessment of gas turbine of turbo shaft engine cycles for an existing simple cycle and its modified cycles using civil helicopter applications carried out by Nkoi (Nkoi *et al*., 2013), the discovered that the performance indices of thermal efficiency, specific fuel consumption, and power output had significant effect on the overall performance of gas turbine engines. They used a software developed at Cranfield University called Turbomatch to carry out the simulation. Some modifications of the gas turbine cycle configurations such as engine cycle with low pressure compressor (LPC), recuperated engine cycle, and intercooled/recuperated (ICR) engine cycle, were also studied and simulated. The performance parameters of the modified cycle engines against the simple cycle were compared, and it was found that the modified engine cycles exhibited better performances in term of thermal efficiency and specific fuel consumption than the traditional simple cycle engine.

Nada (Nada, 2014) carried out performance assessment of an engine with inter-stage turbine burner and compared its performance with another engine employing the nominal reheat concept. The performance indices used in the comparison included intercoolers, recuperator and reheat on a single spool. The engine that had inter-stage turbine burners had much better values in terms of in network and overall efficiency over all other configurations. The best locations for the intercooler and the reheat combustor are determined numerically. The best value of net specific work is obtained when the reheat combustor is placed at 40% of the expansion section. On the other hand, maxtheimum efficiency was obtained when the reheat combustor has to be placed at anywhere between 10% - 20% of the expansion section. The best location of the intercooler was noticed at about 50% of the compression section.

Reviews shows that quite a good number of research has been carried out on gas turbine cycle options for improving engines efficiency and lowering the specific fuel consumption on aircrafts and propulsion engines. These modifications include the incorporations of unconventional components such as intercoolers, regenerators/recuperators and reheaters etc. However, there are few studies on gas turbine cycle modifications for electricity generation, therefore, this study seeks to determine the degree to which these modifications will improve the performance of a local gas turbine power plant.

2. Methodology

The data used for this simulation were obtained from the Omotosho gas turbine power station, using both recorded logbooks and from interviews of staff.. The station is located in Omotosho, Ondo State, Nigeria. It comprises of eight GE Frame turbines. The installed capacity of each machine is 41.875 MW at ISO conditions with a total installed capacity to 335 MW. However, its capability at Nigerian atmospheric conditions is estimated at 38MW each for a total of 304MW.

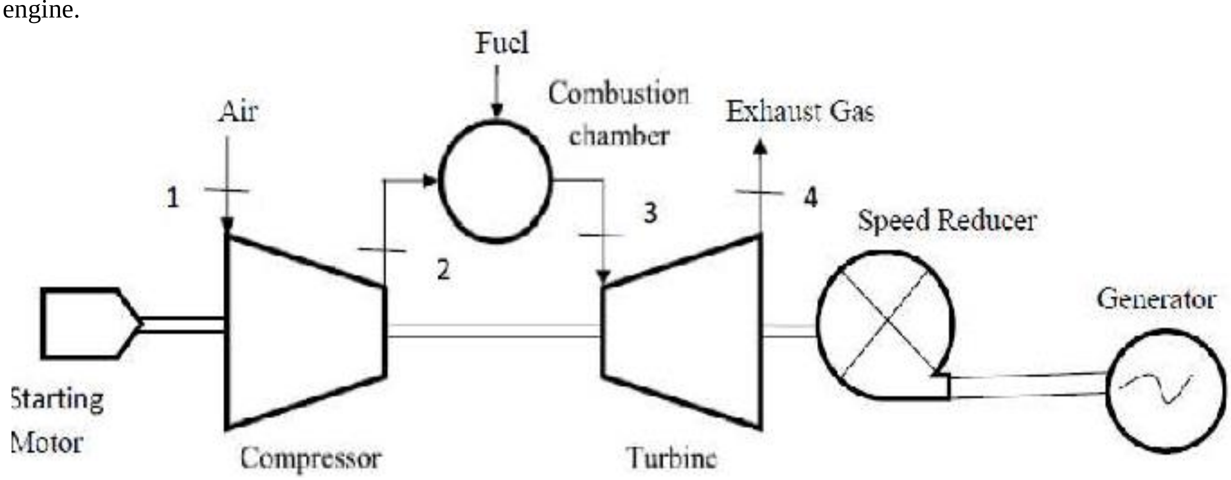
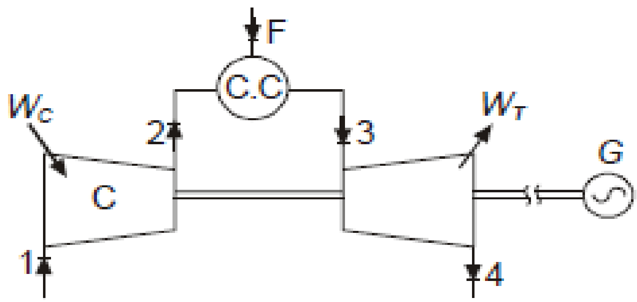


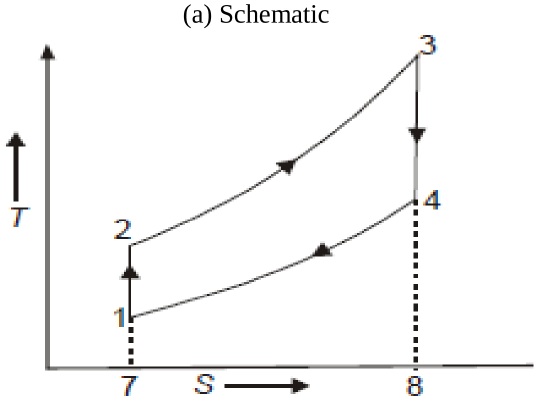
Figure 1 Schematic Diagram of Omotosho Phase I Thermal Power Plant.

The simulation of the power station is carried out using the DWSIM software. DWSIM is a CAPE-OPEN chemical process engineering simulator which is able to simulate steady-state thermodynamic processes.. The gas power plant was modeled using the available unit operations of the simulator, which are represented by blocks or icons. They include Heaters, expanders, coolers, mixers, reactors, heat exchangers, compressors, material streams. The gas turbine is modeled in steady state, that is, under the assumption that its operations are constant with time, hence start-up and shut-down fluctuations are neglected.

Available data from Omotosho gas power plant revealed that the plant has an operating capacity of 288MW (8 x 36MW), a pressure ratio of 10:1, air and fuel mass flow at that operating point are 139.22kg/s and 2.42kg/s respectively (Specifications). With the assumption the turbine expands the combustion gases to atmospheric pressure and that combustion is 100% efficient, the Turbine Inlet Temperature (TIT) was calculated.



(a) Schematic



(b) T-s diagram

Figure 2: Omotosho power plant schematic and T-s diagram

The modeling of the existing simple gas turbine power plant in Omotosho is carried out with the following equations

$$W_C = \dot{m}_a c_{pa}(T_2 - T_1) \quad (1)$$

$$W_T = \dot{m}_g c_{pg}(T_3 - T_4) \quad (2)$$

$$W_{net} = W_T - W_C \quad (3)$$

Heat supplied in the combustion c is given as,

$$q = \dot{m}_g c_{pg} T_3 - \dot{m}_a c_{pa} T_2 \quad (4)$$

Specific fuel consumption is given as

$$sfc = \frac{3600}{W_{net}} \quad (5)$$

Thermal efficiency is given by

$$\eta_{th} = \frac{W_{net}}{q} \quad (6)$$

2.1 Model Validation

To validate the designed model, the isentropic efficiencies of the turbine and compressor were assumed and then altered iteratively to align simulation results with actual data including the turbine inlet temperature, power output and the exhaust gas temperature.

The components of the gas power plant were modeled using the blocks of the simulator and connecting them with the material streams as shown in Figure 3.

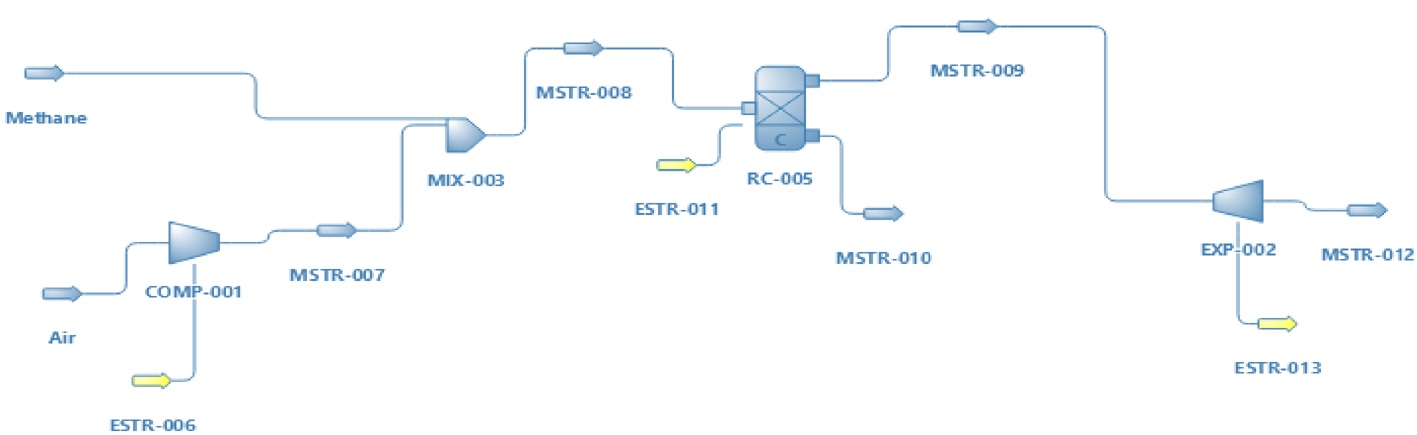


Figure 3: DSWIN schematic of the simple cycle

The model design parameters, parameters from available data are juxtaposed in the table below as applied for the simple cycle design. The results and the percentage deviation are shown in Table1.

Table 1: Model Parameters and Validation Results

Parameters			
Design Parameters	**Model Design Values**	**Actual Values**	**Deviation %**
Air mass flow rate	139.22kg/s	139.22kg/s	-
Fuel mass flow rate	2.42kg/s	2.42kg/s	-
Pressure ratio	10:1	10:1	-
Turbine Isentropic Efficiency	87%	-	-
Compressor Isentropic Efficiency	81.5%	-	-
Combustion Chamber Pressure drop	2%	-	-
Air inlet temperature	25ºC	25ºC	-
Air inlet Pressure	1bar	1bar	-
Results			
Turbine Inlet Temperature	1064.1ºC	1063.041ºC	0.0996
Compressor Power	47.56MW	47.425MW	0.2847
Turbine Power	83.45MW	83.825MW	0.4474
Compressor Discharge Temperature	358.225ºC	364ºC	1.5865
Exhaust gas Temperature	573.45ºC	547ºC	4.8355
Power Output	36.5MW	36.4MW	0.2747
Thermal Efficiency	28.53%	28.4%	0.4578
Specific Fuel Consumption	238.679kg/MWh	239.34kg/MWh	0.2762
Work Ratio	0.4342	0.4340	0.0461
Back Work Ratio	0.5658	0.5660	0.0353

As can be seen from the Table, there is good agreement between the actual design values and the model values.

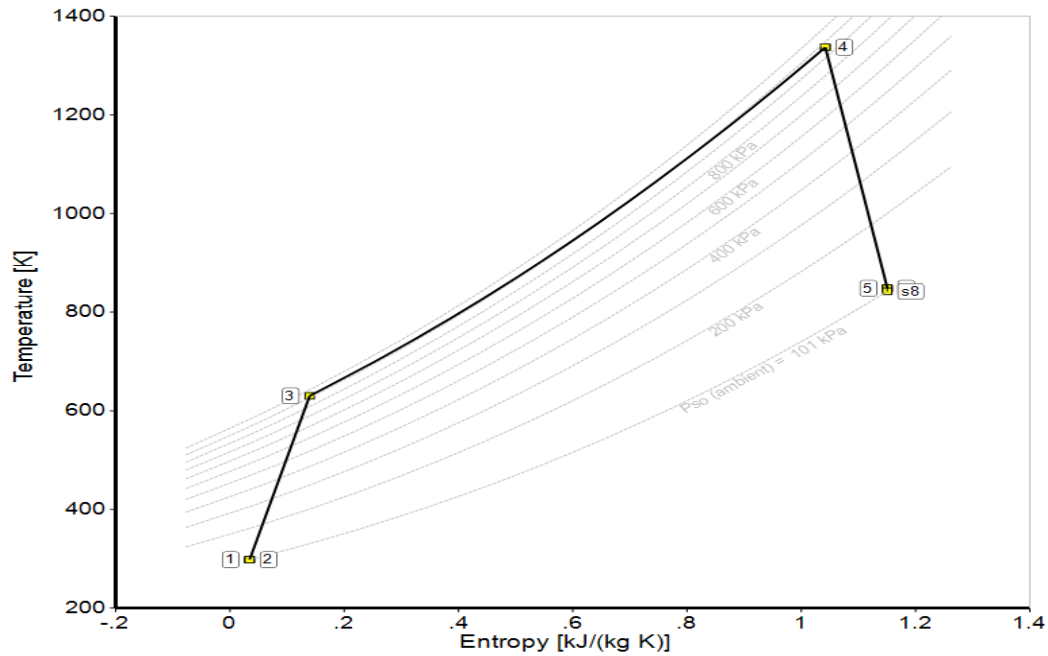


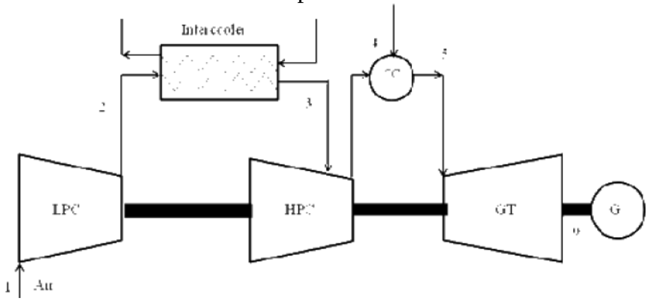
Figure 3 The Plotted T-S Diagram of the Validated Simple Cycle Power Plant

2.2 Modifications to the Simple Cycle

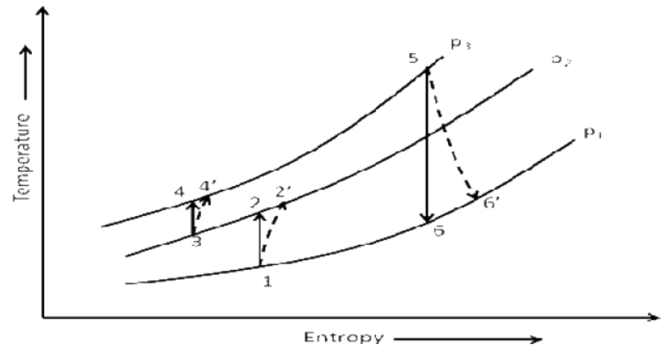
In order to improve the efficiencies of the existing simple cycle in the Omotosho Power Station, modification components such as intercoolers, regenerators and reheaters are introduced. Although these components will increase cost, however, the possibility of reduced fuel and increased efficiencies may offset the cost. The description of these modifications are outlined below:

1.2.1 Simple Cycle Retrofitted with Intercooler (SC-IC)

An intercooler was retrofitted between two compressors representing the high-pressure compressor (HP) and low-pressure compressor (LPC) i.e. the compression process was broken into two stages at the optimum intermediate pressure with the same overall pressure ratio as the simple cycle. The intercooler was allowed to reduce the temperature of the low-pressure compressor outlet air back to the temperature of its inlet which is the room temperature of the 25°C



(a) Schematic diagram



(b) T-s diagram

Figure 4 Schematic and T-s of Intercooling gas turbine cycle

The total work required entire compressor (c) is given by:

$$W_C = W_{hpc} + W_{lpc} = c_{pa}(T_4 - T_3) + c_{pa}(T_2 - T_1) \quad (7)$$

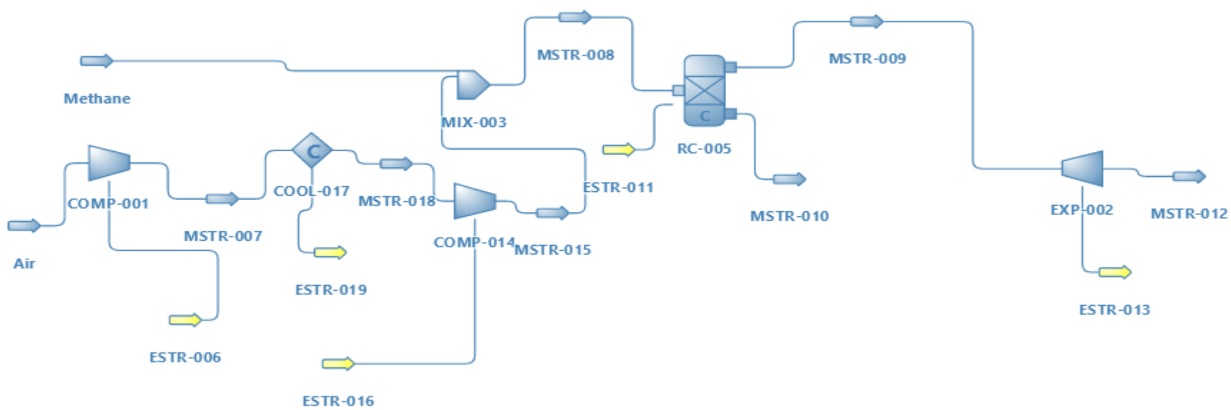


Figure 5: DSWIN schematic of the intercooled cycle

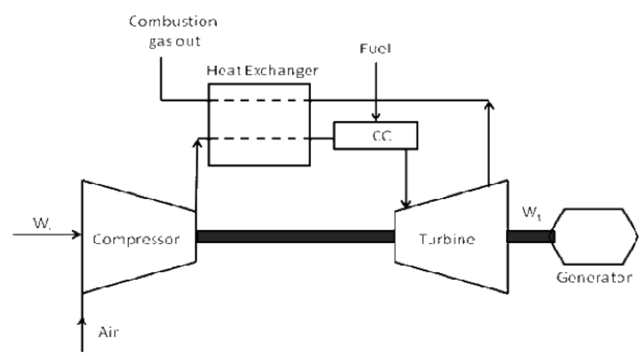
Additional parameters and the results obtained from the simulation are presented in table 2.

Table 2: Parameters and Results for Retrofitted cycle with Intercooler

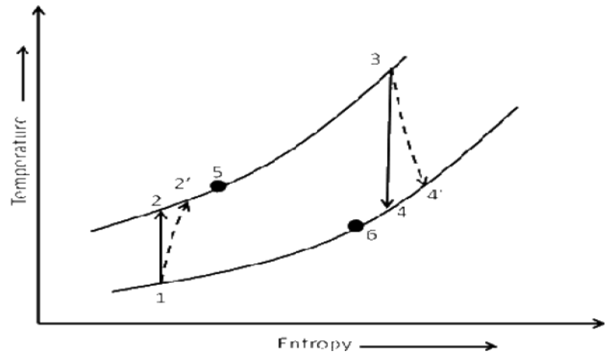
Additional Parameters	**Values**
Intercooler pressure drop	2%
Low-pressure Compressor Pressure Ratio	3.162
Overall Pressure Ratio	10
Results	
Total Compressor Power	40.259MW
Turbine Power	73.882MW
Power Output	33.623MW
Specific Fuel Consumption	259.108kg/MWh
Thermal Efficiency	26.282%
Work Ratio	0.4551
Back Work Ratio	0.5449

1.2.2 Simple Cycle Retrofitted with Regenerator (SC-IC)

In this modification, a regenerator is introduced. The exhaust gases from the turbine are passed through the regenerator which is modeled like a simple heat exchanger and it heats up the compressed air before it enters the combustion Chamber. The pressure drop in the combustion chamber stays the same and a 2% pressure drop is allowed through the heat exchanger.



(a) Schematic diagram



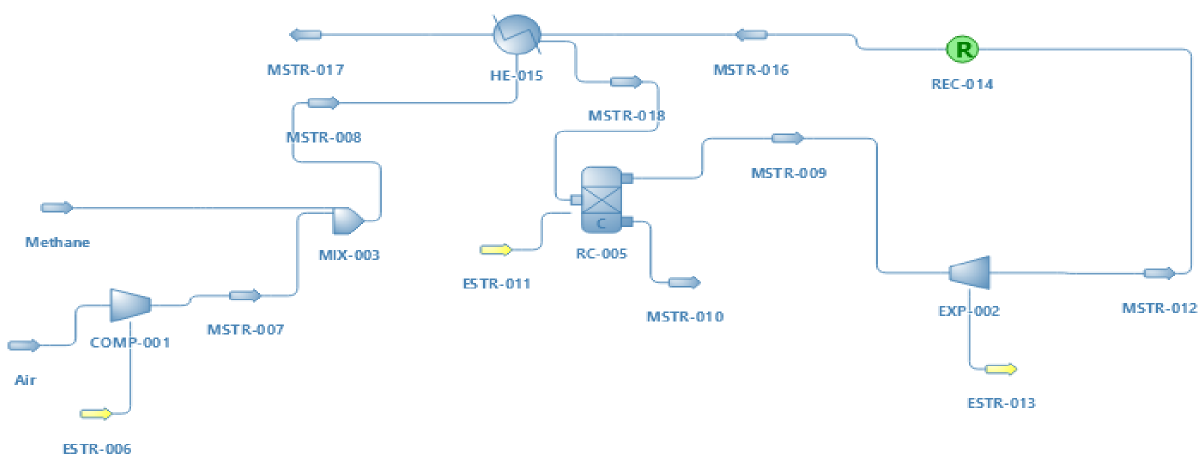
(b) T-s diagram

Figure 6: Schematic and T-s of a Regenerative gas turbine

The regenerator effectiveness is given by:

$$\varepsilon_{rc} = {(T_5 - T_2)}\big/{(T_4 - T_2)} \qquad (8)$$

1.2.3



1.2.4

Figure 7: DSWIN schematic of the regenerated cycle

Table 3: Parameters and Results for the Regenerated Cyclex

Additional Parameters	**Values**
Reheater pressure drop	2%
High-pressure turbine Pressure Ratio	3.162
Overall Pressure Ratio	10
Results	
Total Turbine Power	94.86MW
Compressor Power	47.56MW
Power Output	47.286MW
Case1: No Supplementary Firing	
Thermal Efficiency	26.88%
Specific Fuel Consumption	253.518kg/MWh

1.2.5 2.23 Gas turbine analysis with Reheat.

The reheater in gas turbine cycles is used to raise the power output of the cycle by increasing the turbine generated power. It is known that the power generated by the gas turbine depends on the temperature of these flue gases, hence to harness more power from the gases, the expansion process is broken into stages. In between these stages, it is reheated to a desired temperature – most often to the maximum temperature of the cycle.

Reheating these flue gases can either be through the use of the already operating combustion chamber or with an entirely new combustion chamber. With the fuel type and temperature change of the gases known, the amount of fuel used to reheat the gases can be calculated thus,

$$Q_{reheat} = m_f C_{pg} \Delta T \qquad (9)$$

$$m_f = {Q_{reheat}}\big/{LHV} \qquad (10)$$

The calculated value of mass of fuel can then be used to determine the Specific Fuel Consumption of the gas cycle.

Table 4: Parameters and Results for the Regenerated Cycle

Additional Parameters	**Values**
Reheater pressure drop	2%
High-pressure turbine Pressure Ratio	3.162
Overall Pressure Ratio	10
Results	
Total Turbine Power	94.86MW
Compressor Power	47.56MW
Power Output	47.286MW
Case1: No Supplementary Firing	
Thermal Efficiency	36.96%
Specific Fuel Consumption	184.238kg/MWh
Case 2: With Supplementary Firing	
Thermal Efficiency	26.88%
Specific Fuel Consumption	253.518kg/MWh

1.2.6 Reheater and Regenerator Integrated (RH-RC)

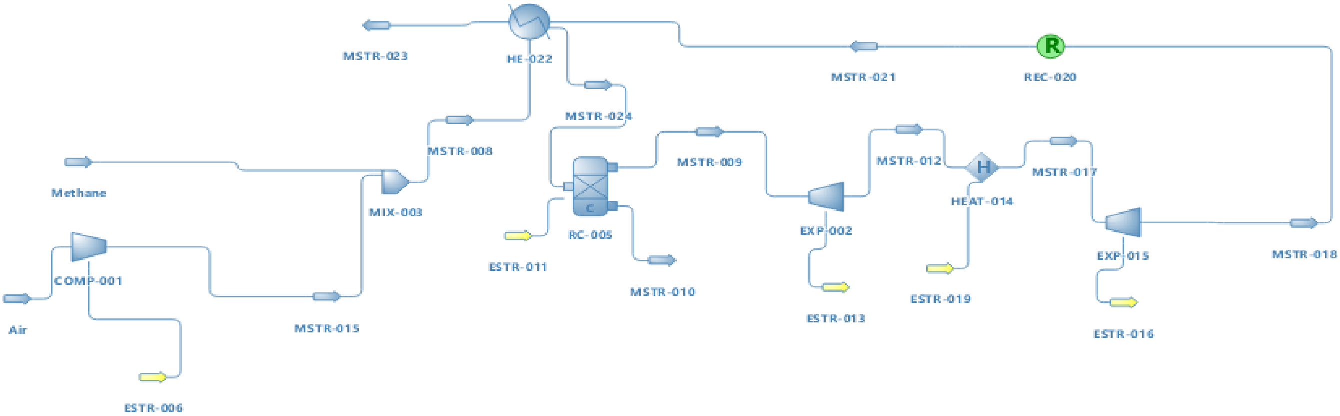


Figure 8 DWSIM Schematic of Reheater and regenerator Integrated

In this cycle modification, the study of the performance variation of the gas cycle of the power plant when a reheater and a regenerator are introduced, is done. The parameters are the same as when these components operated solely. The results obtained are shown in the table below.

Table 5: Results for the Integrated Reheated and Regenerated Cycle

Results	**Values**
Compressor Power	47.57MW
Total Turbine Power	150.873MW
Power Output	103.305MW
Back Work Ratio	0.315
Work Ratio	0.685
Case 1: With Supplementary Firing	
Thermal Efficiency	58.72%
Specific Fuel Consumption	116.045kg/MWh
Case 2: Without Supplementary Firing	
Thermal Efficiency	80.75%
Specific Fuel Consumption	84.333kg/MWh

1.2.7 Intercooler and Regenerator Integrated (IC-RC)

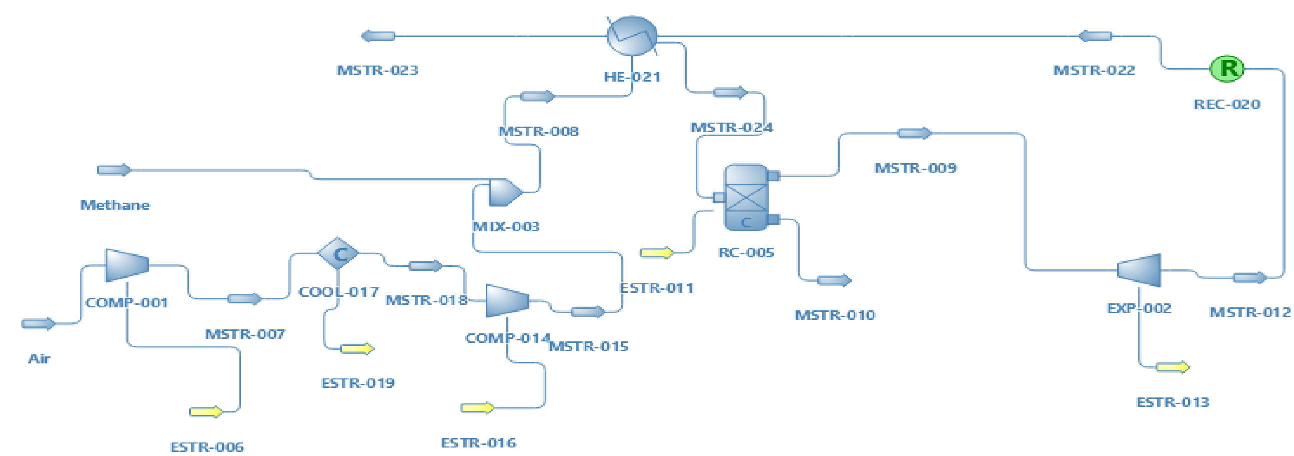


Figure 9 DWSIM Schematic of Intercooler and Regenerator integrated

To the base cycle, both intercooler and regenerator are retrofitted are their usual positions and it is simulated at design point. All efficiencies of the turbines and compressors are kept constant as well as the pressure drops across the intercooler and the regenerator when they operate alone.
Table 6: Results for the Integrated Intercooled and Regenerated Cycle.

Table 6: Results for the Integrated Intercooled and Regenerated Cycle

Results	**Values**
Total Compressor Power	40.2594 MW
Total Turbine Power	109.636 MW
Power Output	69.3766 MW
Work Ratio	0.6328
Back Ratio	0.3672
Thermal Efficiency	54.230%
Specific Fuel Consumption	125. 575kg/MWh

1.2.8 *Intercooler, Regenerator and Reheater Integrated (IC-RH-RC)*

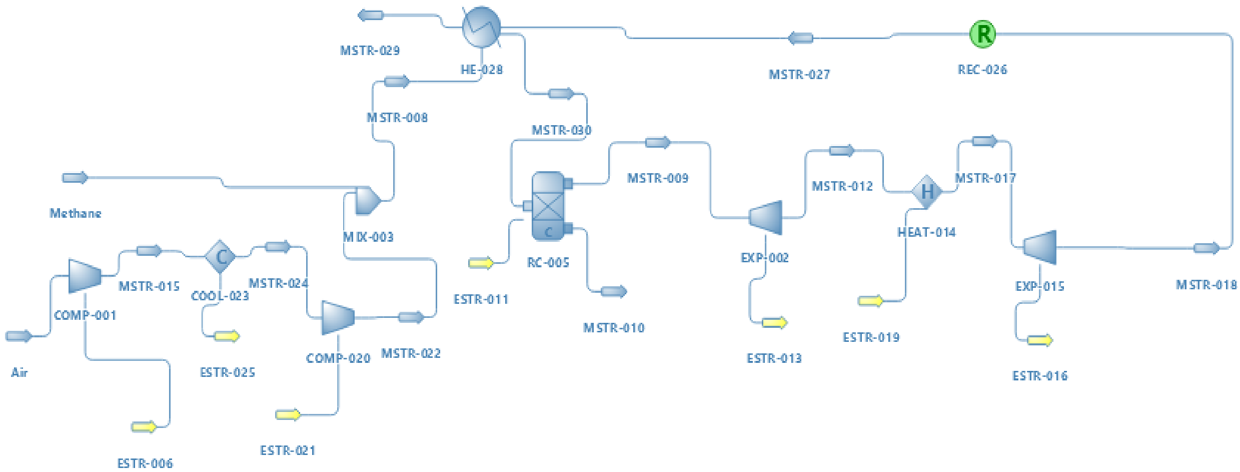


Figure 10 DWSIM Schematic of Intercooler, reheater and recuperation incorporated

All three modification components are combined in this final configuration and the simulation is run to get the performance parameters required for the study.

Table 7: Results for the Integrated Intercooled, Reheated d Regenerated Cycle

Results	**Values**
Compressor Power	40.2594MW
Total Turbine Power	144.034MW
Power Output	103.771MW
Back Work Ratio	0.280
Work Ratio	0.720
Case 1: With Supplementary Firing	
Thermal Efficiency	60.95%
Specific Fuel Consumption	111.708kg/MWh
Case 2: Without Supplementary Firing	
Thermal Efficiency	81.11%
Specific Fuel Consumption	83.954kg/MWh

3. Results Discussion

3.1 Thermal Efficiency

From the model simulation results presented in Tables 1-7 and Figures 11, it can be observed that the most of the modified cycles led to an increase in thermal efficiency with the intercooled regenerated reheat cycles have the best improvement of 64.8% except for those of the intercooled (SC-IC), supplementary firing reheat (SC-RH II) and intercooled-reheat with supplementary firing(IC-RH II) which had reduced efficiencies by 7.4%, 5.68% and 10.8% respectively. This is because intercoolers deliver air to the combustion chamber at reduced temperatures thereby reducing the heat available for expansion in the turbine which leads to a reduction in the power output from the turbine, also reheat with supplementary firing increases the mass flow of the fuel thereby reducing the thermal efficiency of the plant

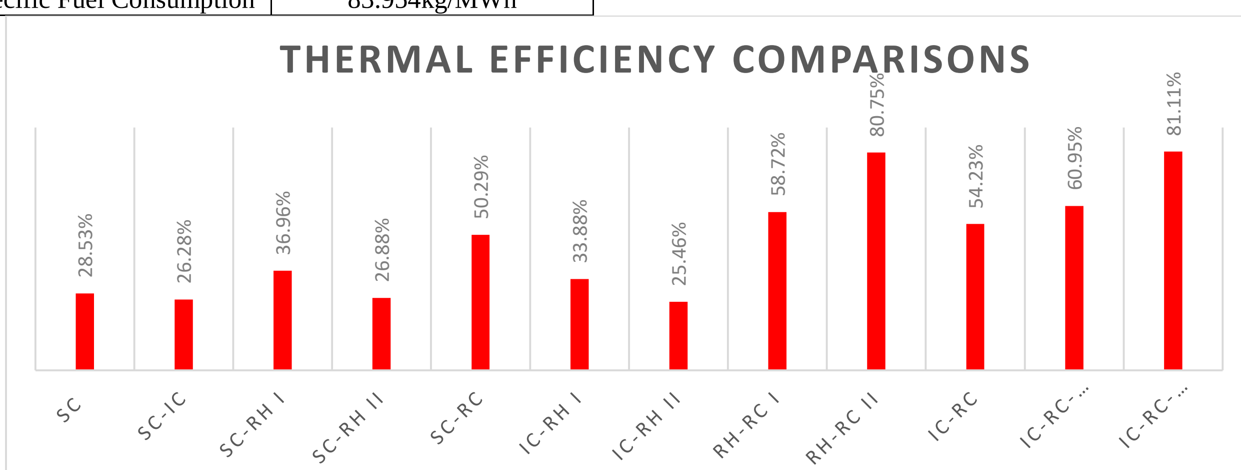


Figure 11: Chart of Gas Turbine Cycles – Thermal Efficiency Comparisons.

3.2 Specific Fuel Consumption

From the model simulation results presented in Tables 1-7 and Figures 12, significant improvements is noticed in most of the modified cycles in terms of the fuel consumption except for those of intercooled (SC-IC), supplementary firing reheat (SC-RH II) and intercooled-reheat with supplementary firing(IC-RH II) where increased fuel consumption by 7.9%, 5.85% and 10.75% respectively were observed

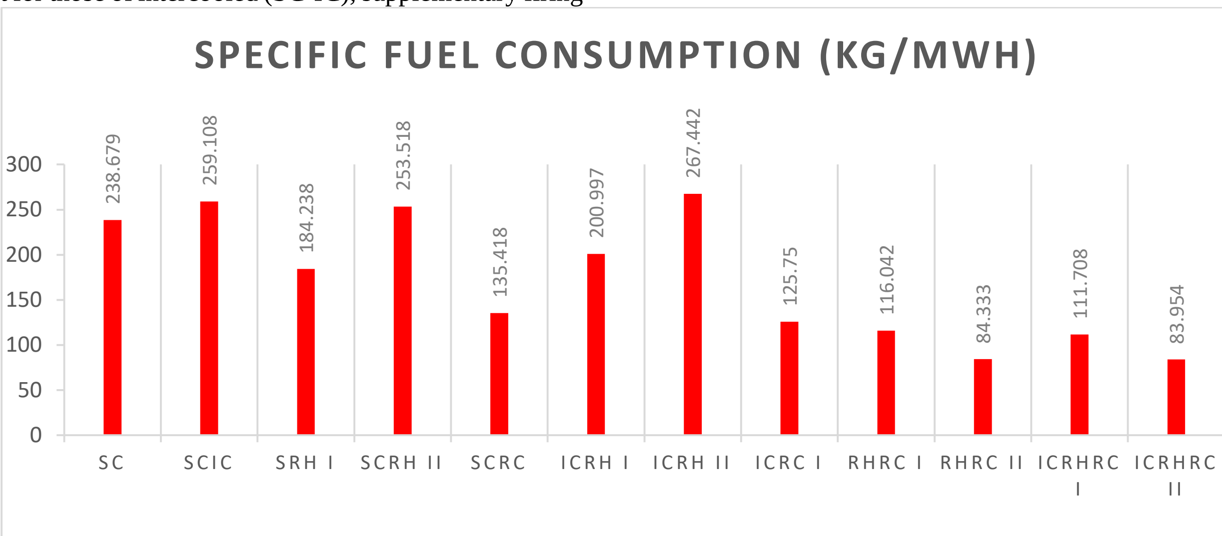


Figure 12: A Chart of Gas Turbine Cycles – Specific Fuel Consumption Comparisons.

3.3 Power Output

From the model simulation results presented in Tables 1-7 and Figures 13, there was marked improvement of power output in all the modifications except for that of the intercooled cycle (SC-IC) which showed in reduction due to the increased compressor work. The power output reduced by 7.9%

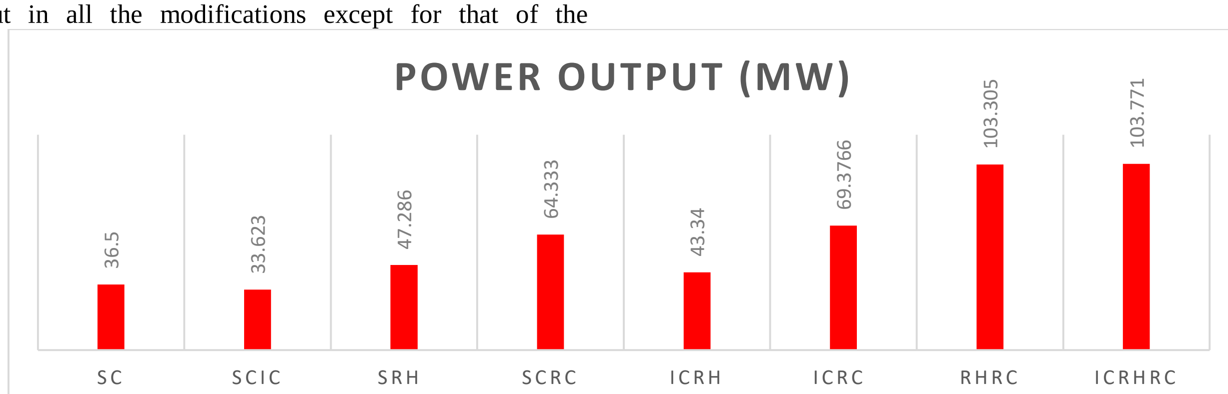


Figure 4.12 A Chart of Gas Turbine Cycles – Power Output Comparisons.

Although introducing these components increase the complexity and manufacture of these power plants, they have a complementing effect on one another. The combination of both intercooler and reheater (with supplementary heating) yielded a thermal efficiency of 25.46%. Including the regenerator to this set up, lifts this thermal efficiency to over 60%.

4. Conclusion

DWSIM software based on the thermodynamic performance of gas turbine was applied to simulate the existing simple cycle of the Omotosho Power Station, Nigeria and some retrofitted modified cycle configurations such as intercooled, regenerative and reheat with some combination options. The results of the performance parameters for the simple cycle compared favorably with the design performance of the power plant. It is seen that to a significant extent, the modified cycles exhibit better performance in terms of the thermal efficiency, specific fuel consumption and power output that the traditional simple cycle, with percentage increases ranging up to 69% increase in some cases.

The performance improvements for some of the configurations are not feasible for practice, either because of their complexity or cost of production which are not offset by the benefits provided by its performance improvements. Also, some modifications lead to an overall decrease in the performance of the power plant, such as introducing intercoolers alone, as seen. Hence this comparative

assessment study provides data to show the degree of performance improvements of the various cycle modifications as well as the proper modifications to the cycles of gas power plants.
It is recommended that for each of these configurations of power plant cycles, an economic analysis is done in order to understand if the cost as a result of complexity offsets the better performances benefits.

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