

REVIEW OF OPERATIONAL THERMODYNAMIC CYCLES OF GRID CONNECTED THERMAL POWER PLANT IN NIGERIA

Isiaka Isah

Center for Atmospheric Research-National Space Research and
Development Agency,
Prince Abubakar Audu University,
Campus Ayingba, Kogi State, Nigeria.
informisah@yahoo.com

Wunuken Carlos Solomon

Department of Mechanical Engineering,
Nigerian Defence Academy (NDA),
Kaduna State, Nigeria.
scwunuken@nda.edu.ng

Bonet Mathias Usman

Department of Aerospace Engineering,
Air Force Institute of Technology (AFIT),
Kaduna State, Nigeria.
mubonet@nda.edu.ng

Samuel Mary, Wunuken Carlos Solomon

Department of Mechanical Engineering,
Nigerian Defence Academy (NDA),
Kaduna State, Nigeria.
m.samuel@nda.edu.ng

Linus Adache Linus

Department of Mechanical Engineering,
Air Force Institute of Technology (AFIT),
Kaduna State, Nigeria.
linusadache@gmail.com

Bankong Daniel Bankong

Department of Mechanical and Aerospace Ground Engineering,
Air Force Institute of Technology (AFIT),

Kaduna State, Nigeria.

bankongd@gmail.com

Masin Muhammad Masin

Department of Mechanical Engineering,
Federal University of Technology (FUT),
Minna Niger State, Nigeria.

masin.muhammadu@futminna.edu.ng

Alliu Henry Taiwo

Center for Atmospheric Research-National Space Research and
Development Agency,
Prince Abubakar Audu University,
Campus Ayingba, Kogi State, Nigeria.

henrytee107@gmail.com

Musa Jibrin

Center for Atmospheric Research-National Space Research and
Development Agency,
Prince Abubakar Audu University,
Campus Ayingba, Kogi State, Nigeria.

jibrinmusa2019@gmail.com

Omale Adam Lawal

Center for Atmospheric Research-National Space Research and
Development Agency,
Prince Abubakar Audu University,
Campus Ayingba, Kogi State, Nigeria.

omalealawal2012@gmail.com

Akus Rahmatu Ojonugwa

Center for Atmospheric Research-National Space Research and
Development Agency,
Prince Abubakar Audu University,
Campus Ayingba, Kogi State, Nigeria.

negedurahmatu@gmail.com

Abdurraheem Muhammad Imam

Center for Atmospheric Research-National Space Research and
Development Agency,
Prince Abubakar Audu University,
Campus Ayingba, Kogi State, Nigeria.

Anyaoagu Daniel Chinedu

Center for Atmospheric Research-National Space Research and
Development Agency,
Prince Abubakar Audu University,
Campus Ayingba,
Kogi State, Nigeria.
ayadiscoles@gmail.com

Attah Augustine

Center for Atmospheric Research-National Space Research and
Development Agency,
Prince Abubakar Audu University,
Campus Ayingba, Kogi State, Nigeria.
austineedogbo@gmail.com

Abstract: This paper reviews the operational thermodynamic cycles of grid connected thermal power plant in Nigeria. Several studies have been carried out on the simple cycle gas turbine power plant to assess the plant which needs to be modified for improved performance and adopted technologies on them were reviewed. The configurations, technologies, design capacities and locations of various gas turbine power plants in Nigeria have been presented. Research materials such as textbooks, specialized handbooks, journals, technical paper publications and original equipment manuals (OEMs) were utilized for this review. The findings of the review showed that the effects of different operating conditions on the performance parameters were analyzed appropriately and also retrofitting the existing simple cycle gas turbine power plants in the country with steam turbine cycles have been assessed to increase power output production, efficiency in addition to utilizing a single fuel source.

Keywords: Gas turbine, Simple cycle, Retrofitting, Configuration, Thermal efficiency, Power output, Specific fuel consumption

1.0 Introduction

The demand for reliable and efficient electric power supply in Nigeria has led to the need for more gas turbines. Gas turbines are energy conversion systems that convert chemical energy in fuel into mechanical energy for electricity generation. They can also be used in aircraft propulsion, petrochemical industries, and refineries. Gas turbines have the advantage of being able to use various types of fuel and can be easily started and stopped to meet both base and peak energy demands (Fidelis Ibiang Abam et al., 2014).

Gas turbines operate on the Brayton thermodynamic cycle, either in an open or closed cycle configuration. However, the closed cycle is rarely used due to the inability to run it at very high turbine inlet temperatures. Technical difficulties such as heat source technologies, power conversion systems, and the need for a demonstration plant have been identified as challenges for closed-cycle gas turbines (Olumayegun et al., 2017).

The open cycle gas turbine is the most commonly used configuration. It consists of a compressor, a combustion chamber, and a gas turbine coupled to an electric generator. In this mode, air is sucked into the compressor and compressed to a higher pressure and temperature. The compressed air is then directed to the combustion chamber, where fuel is injected for combustion to take place. The products of combustion are then directed to the turbine, causing rotation of the generator and generating electric power as shown in figure 1.

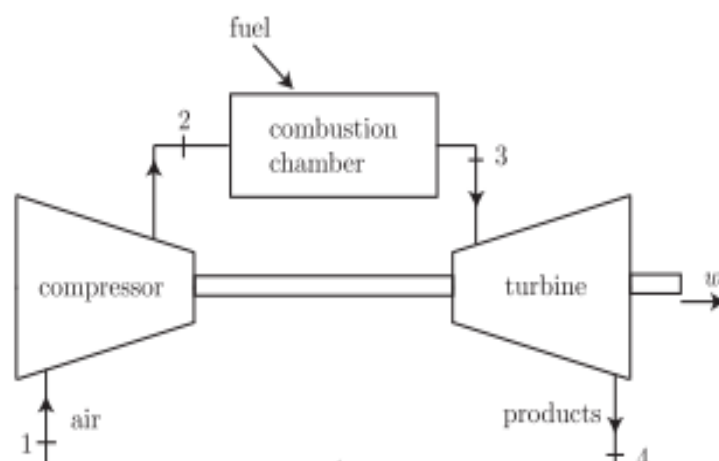


Figure 1: Schematic Diagram of a Simple Gas Turbine (Powers, 2022)

Overall, gas turbines offer numerous benefits such as high-power density, low initial power output, and operation/maintenance cost. However, the closed cycle

configuration faces technical challenges as highlighted earlier, which is why the open cycle is predominantly used.

This article discusses the research that has been conducted on gas turbine technologies, specifically in Nigeria. Most of the gas turbine power plants in Nigeria use a simple cycle configuration, which is known for its low efficiency, low power output, and emission of exhaust gases due to factors such as wears and tears which may have occurred due to age of installation of the gas turbine, over utilization of power developed by the turbine which is used by the compressor because they are both connected with a common shaft, and less utilization of waste heat produced by the turbine emitted to the environment, etc. To overcome these challenges, the article proposes a modification called the Combined Cycle Power Plant (CCPP) shown in figure 2, which combines a gas turbine cycle with a steam turbine cycle. This modification aims to improve thermal efficiency, increase power output, and reduce emission of pollutants to the environment.

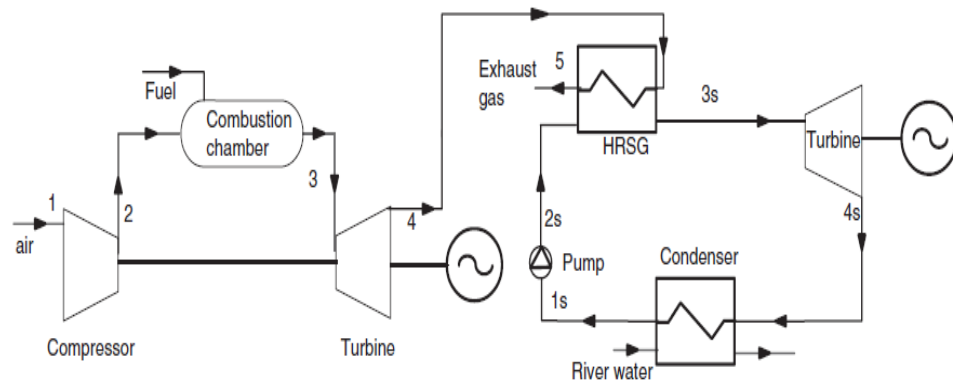


Figure 2: Schematic Diagram of a Combined Cycle Power Plant(Hanafifi et al., 2015)

(Ibrahim et al., 2011), focused on finding the optimum gas turbine configuration for improving the performance of a combined cycle power plant. The researchers analyzed the effects of ambient temperature and compression ratio on the gas turbine configuration and its impact on the performance of the combined cycle power plant. They performed thermodynamic modeling on the major components of the power plant and used MATLAB software for performance analysis. The results of the simulation showed that the simple gas turbine configuration had higher power output, but the regenerative gas turbine configuration had higher efficiency, especially considering the effect of ambient temperature. Further research in this area could potentially lead to more effective

and environmentally-friendly power generation in Nigeria.(Ibrahim & Rahman, 2012), discusses the impact of compression ratio on the performance of Combined Cycle Gas Turbines (CCGT). The authors model the thermodynamic components of the cycle and propose increasing the peak compression ratio as a means of improving CCGT performance. Using MATLAB software, they develop a performance code for CCGT power plants. Simulation results show that increasing the peak compression ratio, as well as low ambient temperature and higher turbine inlet temperature, lead to higher overall efficiency and total power output.(Plant, 2013), presented an article on the effect of ambient temperature on a combined cycle power plant in Dadri, India. The author uses thermodynamic modeling and exergy analysis to analyze the impact of ambient temperature on combined cycle efficiency, gas turbine cycle efficiency, exergy destruction in different components, exergy loss via exhaust, and air fuel ratio.

The results show that for every 1-Degree Celsius increase in ambient temperature, there is a net decrease in combined cycle efficiency of 0.04% and a variation in exergy destruction of different plant components of up to 0.35%.(Mohanty & Venkatesh, 2014), presented a paper on the performance analysis of a combined cycle gas turbine under varying operating conditions. The authors use thermodynamic modeling and a MATLAB simulation software to investigate the effects of parameters such as maximum temperature and pressure of the Rankine cycle, turbine inlet temperature, and pressure ratio of the Brayton cycle on the net output work and thermal efficiency of the combined cycle. The study finds that these parameters have significant influences on the efficiency and work output of the combined cycle.(Ibrahim & Mohammed, 2015), carried out studies that focus on the performance and efficiency of combined cycle gas turbine (CCGT) power plants. They analyzed the effective parameters on the performance of multi-pressure CCGT systems. Using a thermodynamic model, they performed a parametric analysis on an existing CCGT power plant in Saudi Arabia with different pressure configurations. They found that the highest overall power and thermal efficiency was achieved with the supplementary triple-pressure with reheat configuration.(Ibrahim & Mohammed, 2015), conducted a thermodynamic evaluation of a combined cycle power plant. They used energy analysis and simulation with MATLAB software to predict the performance of the CCGT system.

The results showed that the combined cycle CCGT had an overall thermal efficiency of 58% when certain operating parameters were optimized, including the peak compression ratio and cycle peak temperature ratio. (Bakare, A.O.,

Nasir, A., Abiodun, O. R., and Bako, 2016), presented an operation and performance analysis of a combined cycle gas turbine. They discussed the thermodynamic modeling of the combined cycle and investigated the effects of various operating parameters, such as the maximum temperature and pressure of the Rankine cycle, and the turbine inlet temperature and pressure ratio of the Brayton cycle. Using MATLAB simulation software, they found that increasing the turbine inlet temperature and pressure ratio improved the performance of the cycle, resulting in increased efficiency. Overall, these studies contribute to the understanding of the factors influencing the performance and efficiency of combined cycle gas turbine power plants. The findings could be used to design CCGT systems with higher efficiency and output work, ultimately improving the overall performance of these power plants.

Lebele-alawa and Le-ol (2015), discusses the retrofitting of a steam turbine cycle to an existing 25 MW gas turbine plant. This is done by incorporating a heat recovery steam generator (HRSG) to improve performance and reduce emissions. Using thermodynamic equations and MATLAB software, the researchers modeled the parameters of the steam turbine power plant. The results show that the combined cycle system increased the total power output to 37.9 MW, a 51% increase from the steam turbine plant.(Augusto et al., 2016), evaluates the performance of a combined cycle power plant consisting of two gas turbines and a steam turbine. The researchers used MATLAB Simulink® simulation software to develop a control system that can handle unstable grid frequency and ensure the safe operation of the power plant. The results obtained from the simulation allowed for the evaluation of power output, exhaust gas temperature, fuel flow, and variable stator angle during grid instabilities.(Glazar, V., Mrzljak, V. and Gubic, n.d.), conducted a thermodynamic analysis of a combined cycle power plant. The researchers analyzed the size and operating parameters of the plant based on an existing 22 MW gas turbine. They found that increasing the compression ratio initially improved the efficiency of the simple cycle, but further increases led to a decrease in efficiency. However, the thermal efficiency of the simple cycle continued to increase with higher compression ratios. They also observed that higher ambient temperatures decreased thermal efficiency while higher turbine inlet temperatures increased it. Overall, these articles provide insight into the design, performance evaluation, control system development, and thermodynamic analysis of combined cycle power plants.

The findings contribute to the understanding of how to improve efficiency, reduce emissions, and ensure stability in power plant operations. Jaszczur and

Dudek (2019), conducted thermodynamic analysis of a gas turbine combined cycle integration with a high-temperature nuclear reactor. The study analyzed the integration of a high-temperature nuclear reactor with a gas turbine combined cycle. The researchers used mathematical modeling and Epsilon software to conduct a thermodynamic analysis. The results showed that it is possible to achieve cycle efficiency greater than 50% with this combined cycle configuration, which is known for its efficiency and environmental friendliness. (Kahveci, 2006), carried out Energy and Exergy Analysis of Combined-Cycle Power Plant in Turkey. The researchers calculated the exergy of the natural gas and analyzed the exergy losses of each device in the power plant. Based on their analysis, they provided modernization suggestions for improving the energy and exergy efficiency of the plant. Overall, these studies highlight the importance of analyzing and optimizing different factors and operating parameters in combined cycle power plants to improve their efficiency and performance.

These findings contribute to the development of more efficient and environmentally friendly power generation technologies. (Alam et al., 2020), carried out performance analysis and operating parameters of combined cycle power plants. The article discussed the performance analysis of combined gas turbine-steam turbine power generation cycles and the influence of operating parameters on the performance of combined cycle power plants. They performed thermodynamic and exergy analysis of the cycle using different combustion gases under various operating temperatures and pressures. The results showed that combustion chambers, gas turbines, and heat recovery steam generators were the main sources of irreversibility, accounting for more than 85% of the overall exergy losses. Shireef and Ibrahim (2022), investigated the impact of operating parameters on a triple-pressure combined cycle power plant. Energy and exergy analyses were conducted using actual data to assess the plant's performance. The study utilized the Engineering Equation Solver software program. The findings revealed that the net energy and exergy efficiencies of the power plant were 56% and 54%, respectively. Additionally, the combustion chamber was identified as the major source of exergy destruction, accounting for 58% of the total destruction in the plant.

Abam et al. (2011), performed a thermodynamic assessment of grid-based gas turbine power plants in Nigeria. They conducted energy analysis, exergy analysis, and component modeling to evaluate the effect of daily operating data on the plants' performance parameters. Unfortunately, the specific findings and

conclusions of this study were not provided in the summary. Hanafi et al. (2015), examines a combined cycle MEDTVC desalination system. Using a thermodynamic modeling approach and simulation software, the authors analyze the thermal performance and environmental impact of the system. The results indicate that the combined cogeneration system could save around 20.6% of the Total Annual Cost (TAC) compared to separate power and water production systems. (Blumberg et al., 2017), carried out a comparative exergoeconomic evaluation on the latest generation of combined cycle power plants. The researchers compare the triple pressure F-Class and H-Class technologies of Siemens AG. They perform exergy, economic, and thermodynamic analyses using MATLAB and Epsilon for simulation.

The results reveal that the H-Class technology has a higher exergetic efficiency of 58.3% compared to the F-Class with 56%. Additionally, the net present value (NPV) of the H-Class technology outperforms the F-Class by 69% after 20 years of operation. Ighodaro and Osikhuemhe (2019), investigated the thermo-economic analysis of a heat recovery steam generator combined cycle in the Ughelli Power Station. This study focuses on performance and cost analysis of a retrofitted cycle. The authors conduct energy and cost analyses to identify areas for improvement. The findings of this study suggest that optimizing the heat recovery steam generator combined cycle could lead to significant improvements in performance and cost efficiency.

The article by Fakhari et al. (2021), discusses the analysis and optimization of a triple-pressure combined cycle power plant with steam injection in the combustion chamber. The study aims to control the emission of dangerous pollutants, specifically NO_x, while also improving the overall performance and efficiency of the power plant. The researchers used thermodynamic modeling to conduct energy, exergy, economic, and environmental analyses of the system. In another article by Bori et al. (2022), a techno-economic analysis of combined cycle power plants (CCPPs) for electricity generation in Nigeria is presented. The study examines the profitability of CCPPs for increasing electricity production in Nigeria using the Afam VI power station as a case study. The researchers evaluate the economic viability of installing CCPPs with capacities of 1000 MW and 1500 MW. However, the focus of the present study is to carry out a review of operational thermodynamic cycles of grid connected thermal power plant in Nigeria.

2.0 Materials and Methods

The study was a thorough review of the gas turbine technology in Nigeria. It involves an evaluation of several research materials such as textbooks, specialized hand books, journals/articles, technical publications and original equipment manuals (OEM), which were sourced online and, in the libraries, to assess various technologies used by each gas turbine power plant in Nigeria.

Several technologies to improve the performance of the gas turbine cycles were outlined with retrofitting of the existing simple cycle gas turbines with steam turbine cycles offering an improved cycle performance. Through utilization of exhaust waste heat, efficiency and power output can be increased and utilization of single fuel source can be enhanced. In identifying existing gap to be filled, it was discovered that a good number of the existing simple cycle gas turbines currently operating in Nigeria could be configured to combined cycle power plants for improved cycle performance and efficiency.

3.0 Results

Table 1: Gas Turbine Stations in Nigeria showing their Locations(NESP, 2015; Igwe, 2021)

S/NO	POWER PLANT/LOCATION	TECHNOLOGY	CAPACITY (MW)	YEAR ESTABLISHED
1	AES Barge (IPP), Egbin Lagos	Simple cycle gas turbine	280	2001
2	Aba Power Station, Abia State	Simple cycle gas turbine	140	2012
3	Afam IV-V Power Plant, Rivers	Simple cycle gas turbine	724	1982
4	Afam VI Power Station (IPP), Rivers	Combined cycle gas turbine	650	2009
5	Alaoji Power Station (NIPP), Abia State	Combined cycle gas turbine	504	2015
6	Calabar Power Station (NIPP), Cross-River	Simple cycle gas turbine	562.5	2014
7	Egbema Power Station (NIPP), Imo	Simple cycle gas turbine	338	2011

8	Egbin Thermal Power Station-Privatized	Gas-fired steam turbine	1320	1985-1986
9	Geregu, I Power Station-Privatized, Kogi	Simple cycle gas turbine	414	2007
10	Geregu II Power Station (NIPP), Kogi	Simple cycle gas turbine	434	2012
11	Ibom Power Station (IPP), IkotAbasi	Simple cycle gas turbine	190	2009
12	Ihovbor Power Station (NIPP), Benin City	Simple cycle gas turbine	450	2012-2013
13	Okpai Power Station (IPP), Okpai	Combined cycle gas turbine	480	2005
14	Olorunsogo Power Plant, Olorunsogo	Simple cycle gas turbine	500	2008
15	Olorunsogo II Power Plant (NIPP), Olorunsogo	Combined cycle gas turbine	675	2012
16	Omoku Power Station (IPP), Omoku, Rivers	Simple cycle gas turbine	150	2006
17	Omoku II Power Station (IPP), Omoku Rivers	Simple cycle gas turbine	225	
18	Omotosho, I Power Station (FGN-Privatized), Omotosho	Simple cycle gas turbine	785	2005
19	Omotosho II Power Station (NIPP), Omotosho	Simple cycle gas turbine	500	2012
20	Sapele Power Station-Privatized, Sapele	Gas-fired steam turbine & Simple cycle gas turbine	504	1981
21	Sapele Power Station (NIPP), Sapele	Simple cycle gas turbine	450	2012
22	TranscorpUghelli Power Station, Ughelli	Simple cycle gas turbine	942	1966-1990
23	Ibom Power Plant (AKSG), IkotAbasi	Combined cycle gas turbine	191	2010
24	Azura Power Station (IPP), Benin City	Simple cycle gas turbine	450	2018

25	Gbarain Power Plant, Bayelsa	Simple cycle gas turbine	252	
26	Trans-Amadi (IPP), Rivers	Simple cycle gas turbine	136	
27	RusalAlscn Power Station, IkotAbasi	Simple cycle gas turbine	534	1997

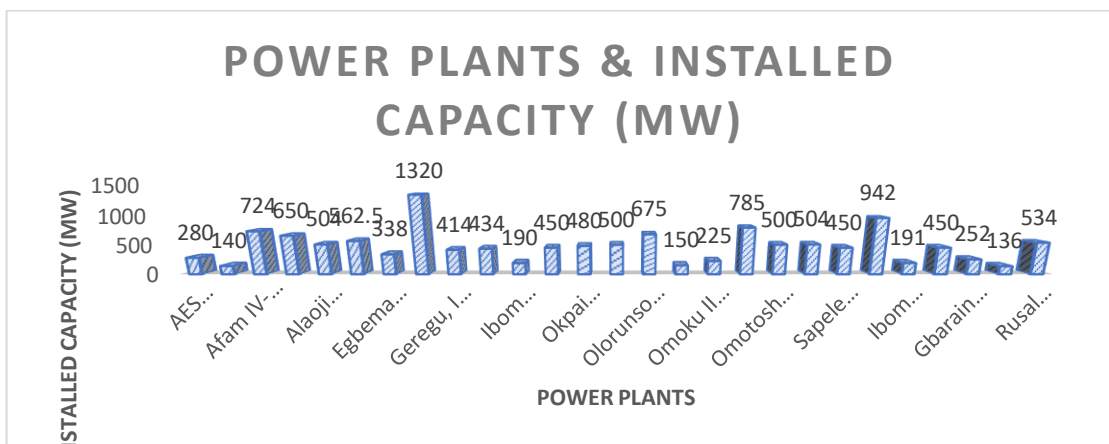


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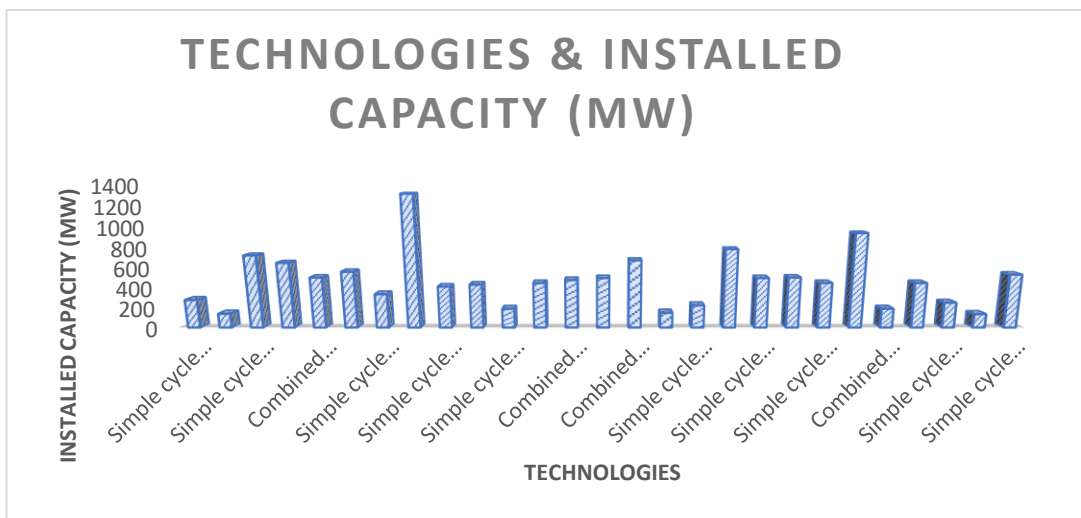


Figure 3:

Table2: Summary of Power Plant Configurations and Percentage Installed Capacity

Technologies	Capacity (MW)	Percentage (%)
Simple Cycle	7804	66
Combined Cycle	4064	34
Total	11868	100

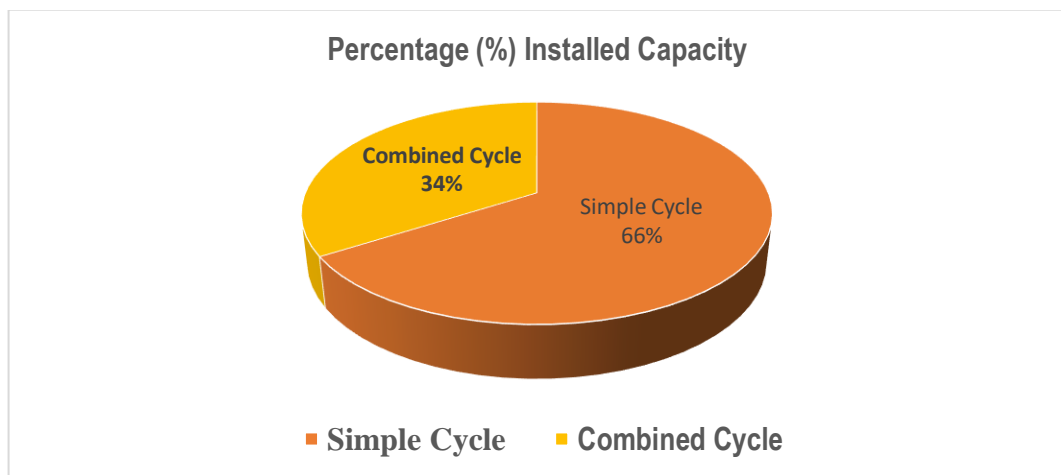


Figure 4: Percentage (%) Installed Capacity

3.1 Discussion

Table 1 presents gas turbine power plants in Nigeria showing their locations, configurations, installed capacities of power generation and their years of establishment. It should be noted that the available power generated presently in Nigeria may be far lower than the total (combined) installed capacity in the Table 1. This is because some of the power plants were not established or operational as at the time those studies were conducted. Therefore, this present study is based on the total installed capacity shown in the Table 1 which does not represent or reflect the actual megawatt of generated power output in Nigeria.

Similarly, Figs 2 and 3 present various power plants and their technologies versus installed power generation capacity. It can be observed from the study that the two technologies used for thermal power generation in Nigeria are simple open cycle and combined cycle respectively. From the Figs 2 and 3, Egbin, operating

on gas-fired steam cycle and Transcorp, operating on simple cycle power plants have the highest installed capacities of 1320 and 942 MW respectively while the Aba, and Trans-Amadi, both operating on simple cycle have the least installed capacities of 140 and 136 MW each.

Furthermore, Table 2 and Fig.4 represent the summary of the power plants configurations and percentage installed capacity. It can however be observed that the total installed capacity for both the simple open and combined cycle power plants was 11868 MW. Out of this, the simple open cycle configurations have total installed capacity of 7804 MW representing 66% as against the combined cycle technologies with total installed capacity of 4064 MW representing 34% respectively.

However, retrofitting the simple open cycle gas turbine with steam turbine unit to a combined cycle power plant will lead to reduction in the emission of exhaust gases from the Brayton cycle to the environment, and also it increases the overall efficiency and power output of the cycle to the national grid.

4.0 Conclusion

This review examined the operational thermodynamic cycles of grid-connected thermal power plants in Nigeria, with emphasis on gas turbine technologies. Findings show that simple cycle gas turbine dominate Nigeria's thermal power sector, accounting for 66% (7804 MW) of total installed capacity versus 34% (4064 MW) for combined cycle configuration. While simple cycles offer advantages such as low initial cost of installation, quick startup and fuel flexibility, they suffer from low thermal efficiency, reduced power output and high exhaust gas emissions due to factors which include ageing equipment, compressor power losses and unutilized waste heat.

Similarly, studies reviewed demonstrate that operating parameters such as ambient temperature, compression ratio, turbine inlet temperature and component efficiencies significantly impact gas turbine performance. Retrofitting existing simple cycle plants with steam turbine cycle to form a Combined Cycle Power Plants (CCPPs) has proven to increase power output by up to 51%, improve overall thermal efficiency to approximately 58%, reduce fuel consumption per MW and lower environmental emissions. CCPPs utilize waste heat from the Brayton cycle to generate additional power via the Rankine cycle, making them a technically viable and economically attractive upgrade for Nigeria's power sector.

Finally, transitioning from simple to combined cycle configurations presents a clear pathway to address Nigeria's demand for reliable, efficient and cleaner electricity generation using existing gas turbine infrastructure.

Recommendations

- (i) **Prioritize retrofitting:** Government and IPP's should conduct techno-economic feasibility studies to retrofit viable simple cycle gas turbine plants, especially high-capacity ones like Transcorp Ughelli, Sapele and Geregu into CCPPs.
- (ii) **Adopt performance optimization:** Implement inlet air cooling, compressor upgrades and advanced control systems to mitigate efficiency losses from high ambient temperatures prevalent in Nigeria.
- (iii) **Standardized monitoring:** Establish mandatory energy and exergy audit protocol for all grid-connected thermal plants to track performance degradation and guide maintenance schedules.
- (iv) **Policy Incentives:** Provide tax breaks, green bonds tariffs for plant that upgrade to combined cycles or achieve set emissions-reduction targets.
- (v) **Update data:** Create a centralized, publicly accessible database of current available capacity versus installed capacity as many plants operate below nameplate ratings.
- (vi) **Environmental compliance:** Mandate NO_x and CO₂ emission benchmarks for all thermal plants, encourage steam injection and other clean combustion technologies.

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