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Evaluation of the Environmental and Social Benefits of Conversion Process of Open Cycle to Combined Cycle Gas Power Plant

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ABSTRACT

Worldwide concern about reducing global warming consequences and combating energy crisis has motivated the development of power generation technologies to move towards sustainable energy production with higher efficiency and low environmental impacts. This study evaluated the environmental and social benefits of converting open-cycle to combined-cycle gas power plants in electric power generating system in Nigeria. All the current operational open and combined cycle gas power plants were considered. Green House Gas (GHG) emission data were collected for both open and combined cycle plants. The results showed that after conversion from open cycle to combined cycle, society bears a lesser cost of generating electricity as there is a minimum difference of 3.78 N/kWh (Calabar NIPP), which is about 23.34% change in cost and a maximum of 4.00 N/kWh (Omotosho Pacific Energy plant), which is about 25.20% change in cost for a minimum range of emission cost (40USD/tCO$_2$e). There is a minimum difference of 8.54 N/kWh (Calabar NIPP), which is about 28.57% change in cost and a maximum of 8.76 N/kWh (Omotosho Pacific Energy plant), which is about 29.64% change in cost for a maximum emission cost (100USD/tCO$_2$e). The study concluded that it costs less to reduce GHG and air pollution damage during the process of conversion from open cycle to combined cycle gas. Also, it is more beneficial to generate electricity using a combined gas turbine, and society bears less cost for higher electricity generation by a combined cycle when compared with an open cycle.

INTRODUCTION

The availability and access to electricity determine a society's economic progress and standard of living. Thus, the significance of expanding access to commercial electrical power must be recognised for any society to thrive sustainably (Mohamed, 2005). Without significant energy consumption, no country in the twenty-first century can effectively alleviate poverty; in fact, the majority of wealthy and human development index-ranking nations also have greater energy consumption rates (Akuru and Animalu, 2009; Akuru *et al.,* 2017). This has led to a greater use of energy than at any previous time in human history, be it for transportation, electricity, or other purposes. In order to propel significant economic growth, a nation's ability to generate electricity must keep pace with its population increase (Onyeisi *et al.,* 2016). It is imperative to note that a country's generation of electricity is very essential for both economic development and quality of life, not only because it can raise labour, capital, and other production-related productivity, but also because rising electricity consumption is a sign of a nation's strong socioeconomic standing (Jumbe, 2004; Adebola, 2011). Therefore, energy, a basic human need, influences economic growth and is now the primary driver of national development.

Poverty is a major social problem in *Nigeria*. It has a direct correlation with Nigeria's energy consumption per capita, which is among the lowest globally and accounts for around one-sixth of that of developed nations (Oyedepo, 2012). It has been demonstrated that the main issue with energy security is the known link between poverty and energy (Kanagawa and Nakata, 2007; Chakravarty and Tavoni, 2013; Monyei et al., 2018). This issue had severe economic effects on the country, causing businesses and industries to run below capacity. The nation's cost of goods and services has increased due to certain businesses turning to diesel generators as a substitute source of electricity, driving up production costs (Adenikinju, 2003; Aladejare, 2014). On the other hand, some industrial and commercial establishments have moved to nearby nations with reliable electrical supplies. According to Madu (2017), the financial benefits of a thriving and expanding electrical sector must be explained in order to calculate the impact of electricity on Nigeria's prospective economic growth and, consequently, calculate the worth of the money that Nigerians will save.

Natural gas is the fuel that is most frequently utilised in Nigeria to generate power using steam and gas turbines because the nation has an abundance of gas reserves (Oluwatoyin et al., 2015; Fadare et al., 2018). Natural gas is burned to generate heat, which in a steam turbine turns water into steam. Heat recovery steam generators (HRSGs) can be used in combined cycle mode to convert gas turbines and steam turbines to achieve higher efficiency. An energy plant that uses the same amount of natural gas to power both gas and steam turbines simultaneously is known as a combined cycle power plant. The most environmentally friendly method of producing power from fossil fuels is through combined cycle power generation with natural gas. The total efficiency of the two cycles is what makes up the combined cycle's efficiency. Fadare and Ilori (2022) established that an extra 1142.1 MW of power could be produced by converting the open-cycle gas power plants in Nigeria to combined-cycle power plants after the technological viability of the conversion was evaluated. These plants' ability to consume gas will not need to increase in order to accommodate this extra generation. This was validated by another work of Fadare et al. (2024) that it is economically feasible to convert gas turbines from open cycle to mixed cycle, and that doing so will allow for the generation of more electricity while maintaining the same gas consumption. These plants exhibit low specific emissions values in addition to their high conversion efficiency, as they release less than half the CO_2 emissions of coal-fired facilities with comparable ratings (IEA, 2011).

A truer and more accurate picture is given by the society's cost of electricity (SCOE), which may be used to arrive at a more realistic assessment of which power generation methods will most benefit Nigerian society today, as well as in the future. Environmental and social externalities are included in the SCOE viewpoint since it is predicated on costs and benefits to society. The price of air pollution damage, the effects of climate change, system integration costs, subsidies, employment consequences, the cost of water pollution and over-extraction, geopolitical hazards, etc. are samples of potential externalities. Unlike levelized cost of electricity (LCOE), which has a well-defined definition, SCOE lacks consistency and might be defined differently by different practitioners. By including quantitative estimates of the externality costs, SCOE expands upon LCOE. The SCOE computation can be more detailed the more data that is available for a given energy system. Although monetary values do not fully reflect all social gains and losses, they have become a more common way to quantify the external costs and advantages of producing energy over the past ten years. Nevertheless, Nigeria has never carried out this. The study's estimate of the cost of air pollution is based on European statistics (DEA, 2018).

Based on the aforementioned, an investigation has been performed on ways of improving the utilisation and increasing the power generation without increasing the gas consumption by converting the open-cycle gas turbine units to combined cycle plants. However, evidence is scarce on the environmental and social benefits associated with the conversion process. Hence, this study evaluated the environmental and social benefits of converting open cycle to combined cycle gas power plants in Nigeria's electric power generating system.

METHODOLOGY

Research Design

The study evaluated the quantities of natural gas saved and the associated greenhouse gases reduced from the open cycle (OC) to combined cycle (CC) gas power plant conversion process in Nigeria's electric power generating system.

Sampling and Study Coverage

The research study examined Nigeria's open-cycle and combined cycle power plants that are currently in operation, using both primary and secondary data sources. With regard to gas turbines, the following companies were specifically taken into consideration: Okpai (Delta), Forte Oil (Kogi), Pacific Energy (Ogun and Ondo), Afam VI (Rivers), and Transcorp Power (Delta), and all active National Integrated Power Project (NIPP) plants.

Parameters for Evaluation of the Environmental and Social Benefits

To determine the environmental and social benefits of converting to combined cycle from open cycle gas turbines, it is necessary to evaluate these parameters as follows:

Simple levelized cost of electricity

The National Renewable Energy Laboratory (NREL) method of simple levelized cost of energy (SLCOE) calculator was used as presented in Equations (1-2).

$$\{(overnight\ capital\ cost \times CRF) + (FOM/(8760 \times capacity\ factor))\} + (specific\ fuel\ cost \times heat\ rate) + VOM \quad (1)$$

$$CRF\ (capital\ recovery\ factor) = \frac{r \times (1 \times r)^i}{(1 \times r)^i - 1} \quad (2)$$

Where,

NERC defined i =11% and r is the weighted average cost of capital

FOM is the annual fixed operation and maintenance costs

VOM is the variable operation and maintenance costs

Society's cost of electricity

The Society's cost of electricity (SCOE) can be determined using Equation 3 below;

$$SCOE = LCOE + cost\ of\ climate\ change\ damage + cost\ of\ air\ pollution\ damage + system\ integration \quad (3)$$

Cost of climate change

To evaluate the cost of climate change, the method by the Energy Information Administration (EIA) of the United States of America USA was used to determine the damage cost of CO_2 emissions on the environmental and social benefits. This is shown in Equation 4.

$$XC_{CO_2} = [DC \times EF]_{CO_2} \times EG \quad (4)$$

Where;

XC is the External Cost (N/MWh)
DC is the Damage Cost (N/ton)
EF is the Emission Factor (ton/MW)
EG is the Energy Generated (MWh)

Cost of air pollution

The variables for each air pollution emission considered for this study were obtained from National Energy Laboratory Technology, USA Department of Energy (NELT, 2013). These values reflect standards used for various studies. The cost of air pollution was calculated using Equations 5-9 below.

$$XC_{SO_2} = [DC \times EF]_{SO_2} \times EG \quad (5)$$
$$XC_{NO_X} = [DC \times EF]_{NO_X} \times EG \quad (6)$$
$$XC_{PM} = [DC \times EF]_{PM} \times EG \quad (7)$$
$$XC_{CO} = [DC \times EF]_{CO} \times EG \quad (8)$$
$$XC_{VOC} = [DC \times EF]_{VOC} \times EG \quad (9)$$

RESULTS AND DISCUSSION

The results of the parameters evaluated on environmental and social benefits of converting to combined cycle from open cycle power plant are discussed under the following headings.

Cost of Climate Change Damage to the Society by Power Plants

Table 1 shows the results obtained on the cost of climate change for the conversion process of the power plants. In order to determine the cost of climate change, it was pertinent to determine the cost of carbon to society, which is connected with significant uncertainties. The range of potential societal costs of carbon selected for this analysis is between 40 and 100 USD/tCO_2e. This range provides a representative sample of potential costs to Nigeria, a nation especially susceptible to climate shocks and trends, particularly droughts and floods. The lower-bound carbon values chosen for this study reflect the cost that the majority of businesses now factor into their long-term and project planning, while the 100 USD/tCO_2e number is suggested to reflect the costs of climate change damage that are already being noticed, drawing from global research (Stiglitz and Stern, 2017).

The result reveals that for Ihovbor open cycle gas power plant, the energy generated is ₦1,576,800.00, while the cost of limiting the greenhouse gas for 40 USD/tCO_2e is ₦14,389,246,080.00 and ₦35,973,115,200.00 for 100 USD/tCO_2e. The conversion process of 337.5 MW for Ihovbor shows that it has a higher energy generation of ₦2,365,200.00 operating in a combined cycle. The cost of climate change reveals that it costs less to reduce greenhouse gas for both 40 USD/tCO_2e at ₦14,081,454,720.00 and 100 USD/tCO_2e at ₦35,203,636,800.00, respectively. Also, the result depicts higher energy generation for Transcorp for combine cycle at ₦4,158,547.20 as compared to open cycle at ₦3,027,456.00. The cost of climate change also reveals that it cost less to limit CO_2 gas in combined cycle at ₦24,758,326,609.92 than open cycle at ₦27,627,352,473.60 for 40 USD/tCO_2e. Also, both Pacific Energy plants show that a greater amount of energy is generated by the conversion process in combined cycle gas power plant and less cost of climate damage to society for the combined cycle than open cycle at 40 USD/tCO_2e (₦14,269,207,449.60) and 100 USD/tCO_2e (₦35,673,018,624.00) for both plants. Additionally, similar results were observed for Omotosho NIPP, Geregu NIPP, Calabar NIPP and Geregu Forte Oil on the cost of climate damage to society for the conversion process of the power plants (Table 1).

Cost of Air Pollution Damage to the Society by Power Plants

Table 2 shows the results obtained for the cost of air pollution from all the gas power plants considered in this study. The results revealed the cost of air pollutants for the various gases emitted, which include CO, NO_X, SO_2, VOC and small particles (PM). The NO_X and VOC have the highest cost of air pollution for both open cycle and combined cycle. This indicates that it cost less to reduce the cost of air pollution damage during conversion process from open cycle to combined cycle.

As presented on Table 2, it cost a total of ₦4,428,885,278.91 to limit air pollution damage for the combined cycle and ₦4,555,328,704.25 for the open cycle for Ihovbor gas power plant. Similarly, Calabar NIPP and Transcorp show higher costs of air pollution damage to society because of their daily generation, both in open cycle and combined cycle. The total air pollution in combined cycle for Calabar NIPP and Transcorp are N8,865,644,131.64 and N7,786,964,517.05, respectively, which is less than the total air pollution cost for open cycle at N9,118,755,770.64 and N8,746,231,112.16, in turn. In essence, the results in Table 2 capture the fact that it is better for gas power plants to operate in combined cycle mode because of its benefit of reducing the total cost of air pollutants damage to the surrounding society.

System Integration Cost for the Gas Power Plants

Table 3 presents results on the system integration cost for the gas power plants for both open-cycle and combined cycle power plants. The results show higher energy generation for the conversion process in combined cycle as compared to open cycle gas power plants. The system cost for the power plants shows different pattern for cost of climate change and cost of air pollution damage to the society. The result presents higher system cost for the conversion process in combined cycle gas power plant than open cycle.

This could be because Ihovbor and Omotosho NIPP gas power plant have a system integration cost of ₦1,635,141,600.00 and ₦1,816,824,000.00, ₦2,452,712,400.00 and ₦2,725,236,000.00 respectively for combined cycle gas plant. The higher value for the cost could be because of the additional cost of equipment required in operating combined cycle gas power plant. Also, Calabar NIPP and Transcorp plant have higher and close values for their system integration cost for both open cycle and combined cycle. This shows that for a daily generation of 675.6 MW and 593.4 MW, the system integration costs are ₦4,909,785,177.60 and ₦4,312,413,446.40, respectively. Also, similar results were shown by Omotosho Pacific Energy and Olorunsogo Pacific Energy with high system cost value in combined cycle.

Levelized Cost of Electricity

Table 4 shows the results obtained for the levelized cost of electricity for the power plants under consideration. The cost of a power asset during its lifespan was calculated using the levelized cost of electricity approach to assess the energy cost to society. Thus, Table 4 shows the daily generation for each power plant, both in combined cycle and open cycle conversion processes, as well as the capacity cost of the power plants, capital recovery factor, fuel cost, heat rate, fixed and variable operation, cost of fuel and maintenance costs. The results revealed that levelized cost of energy for the power plant is higher for the conversion process in combined cycle. The Ihovbor power plant has a levelized cost of energy of N7,034,997,183 for a daily generation of 337.5 MW which is much higher than the value for combined cycle.

Table 1: Cost of climate change for the power plants

Location of power plants	Type of power plant	Daily generation (MW)	Energy generated (Yearly)	Total annual CO_2e emission (tCO_2e)	Cost of emission using 40USD/tCO_2e benchmark	Total cost of emission (₦)	Cost of emission using 100USD/tCO_2e benchmark	Total cost of emission (₦)
Ihovbor	OC	225	1,576,800.00	1,179,446.40	47,177,856.00	14,389,246,080.00	117,944,640.00	35,973,115,200.00
	CC	337.5	2,365,200.00	1,154,217.60	46,168,704.00	14,081,454,720.00	115,421,760.00	35,203,636,800.00
Omotosho NIPP	OC	250	1,752,000.00	1,310,496.00	52,419,840.00	15,988,051,200.00	131,049,600.00	39,970,128,000.00
	CC	375	2,628,000.00	1,282,464.00	51,298,560.00	15,646,060,800.00	128,246,400.00	39,115,152,000.00
Geregu NIPP	OC	290	2,032,320.00	1,520,175.36	60,807,014.40	18,546,139,392.00	152,017,536.00	46,365,348,480.00
	CC	435	3,048,480.00	1,487,658.24	59,506,329.60	18,149,430,528.00	148,765,824.00	45,373,576,320.00
Calabar NIPP	OC	450.4	3,156,403.20	2,360,989.59	94,439,583.74	28,804,073,041.92	236,098,959.36	72,010,182,604.80
	CC	675.6	4,734,604.80	2,310,487.14	92,419,485.70	28,187,943,137.28	231,048,714.24	70,469,857,843.20
Transcorp	OC	432	3,027,456.00	2,264,537.09	90,581,483.52	27,627,352,473.60	226,453,708.80	69,068,381,184.00
	CC	593.4	4,158,547.20	2,029,371.03	81,174,841.34	24,758,326,609.92	202,937,103.36	61,895,816,524.80
Geregu Forte Oil	OC	290	2,032,320.00	1,520,175.36	60,807,014.40	18,546,139,392.00	152,017,536.00	46,365,348,480.00
	CC	435	3,048,480.00	1,487,658.24	59,506,329.60	18,149,430,528.00	148,765,824.00	45,373,576,320.00
Omotosho Pacific Energy	OC	228	1,597,824.00	1,195,172.35	47,806,894.08	14,581,102,694.40	119,517,235.20	36,452,756,736.00
	CC	342	2,396,736.00	1,169,607.17	46,784,286.72	14,269,207,449.60	116,960,716.80	35,673,018,624.00
Olorunsogo Pacific Energy	OC	228	1,597,824.00	1,195,172.35	47,806,894.08	14,581,102,694.40	119,517,235.20	36,452,756,736.00
	CC	342	2,396,736.00	1,169,607.17	46,784,286.72	14,269,207,449.60	116,960,716.80	35,673,018,624.00

Table 2: Cost of air pollution

Location of Power plants	Type of power plant	Daily Generation (MW)	CO (₦)	NO_X (₦)	SO_2 (₦)	VOC (₦)	PM (₦)	Total Air Pollution (₦)
Ihovbor	OC	225	37,272,022.63	3,016,293,654.31	9,981,311.67	1,486,545,091.71	5,236,623.93	4,555,328,704.25
	CC	337.5	35,951,760.25	2,930,603,493.67	9,940,846.89	1,447,292,197.46	5,096,980.63	4,428,885,278.91
Omotosho NIPP	OC	250	41,413,358.48	3,351,437,393.67	11,090,346.30	1,651,716,768.56	5,818,471.04	5,061,476,338.05
	CC	375	39,946,400.28	3,256,226,104.08	11,045,385.44	1,608,102,441.62	5,663,311.81	4,920,983,643.23
Geregu NIPP	OC	290	48,039,495.84	3,887,667,376.66	12,864,801.71	1,915,991,451.53	6,749,426.40	5,871,312,552.14
	CC	435	46,337,824.32	3,777,222,280.73	12,812,647.11	1,865,398,832.28	6,569,441.70	5,708,341,026.15
Calabar NIPP	OC	450.4	74,610,306.64	6,037,949,608.44	19,980,367.89	2,975,732,930.24	10,482,557.42	9,118,755,770.64
	CC	675.6	71,967,434.74	5,866,416,949.11	19,899,366.40	2,897,157,358.83	10,203,022.56	8,865,644,131.64
Transcorp	OC	432	71,562,283.45	5,791,283,816.27	19,164,118.40	2,854,166,576.08	10,054,317.95	8,746,231,112.16
	CC	593.4	63,211,183.80	5,152,652,187.10	17,478,217.91	2,544,661,303.63	8,961,624.61	7,786,964,517.05
Geregu Forte Oil	OC	290	48,039,495.84	3,887,667,376.66	12,864,801.71	1,915,991,451.53	6,749,426.40	5,871,312,552.14
	CC	435	46,337,824.32	3,777,222,280.73	12,812,647.11	1,865,398,832.28	6,569,441.70	5,708,341,026.15
Omotosho Pacific Energy	OC	228	37,768,982.93	3,056,510,903.03	10,114,395.82	1,506,365,692.93	5,306,445.59	4,616,066,420.30
	CC	342	36,431,117.05	2,969,678,206.92	10,073,391.52	1,466,589,426.76	5,164,940.37	4,487,937,082.62
Olorunsogo Pacific Energy	OC	228	37,768,982.93	3,056,510,903.03	10,114,395.82	1,506,365,692.93	5,306,445.59	4,616,066,420.30
	CC	342	36,431,117.05	2,969,678,206.92	10,073,391.52	1,466,589,426.76	5,164,940.37	4,487,937,082.62

Table 3: System integration cost for the gas power plants

Location of power plants	Type of power plant	Daily Generation (MW)	Energy Generated in 1 year (KWH)	System Integration cost (₦)
Ihovbor	OC	225	1,576,800,000.00	1,635,141,600.00
	CC	337.5	2,365,200,000.00	2,452,712,400.00
Omotosho NIPP	OC	250	1,752,000,000.00	1,816,824,000.00
	CC	375	2,628,000,000.00	2,725,236,000.00
Geregu NIPP	OC	290	2,032,320,000.00	2,107,515,840.00
	CC	435	3,048,480,000.00	3,161,273,760.00
Calabar NIPP	OC	450.4	3,156,403,200.00	3,273,190,118.40
	CC	675.6	4,734,604,800.00	4,909,785,177.60
Transcorp	OC	432	3,027,456,000.00	3,139,471,872.00
	CC	593.4	4,158,547,200.00	4,312,413,446.40
Geregu Forte Oil	OC	290	2,032,320,000.00	2,107,515,840.00
	CC	435	3,048,480,000.00	3,161,273,760.00
Omotosho Pacific Energy	OC	228	1,597,824,000.00	1,656,943,488.00
	CC	342	2,396,736,000.00	2,485,415,232.00
Olorunsogo Pacific Energy	OC	228	1,597,824,000.00	1,656,943,488.00
	CC	342	2,396,736,000.00	2,485,415,232.00

The high levelized cost of energy value could be because of combined cycle gas power plant average daily generation capacity which is higher than that of open cycle with difference of 225 MW. The same result applies to the other gas power plants considered for this study. Calabar NIPP and Transcorp with average daily generation of 675.6 MW and 593.4 MW for combined cycle and 450.4 MW and 432 MW in open cycle, had the highest levelized cost of energy value, respectively. This could be due to the average daily capacity generated. The results from this study can be supported by the reports of Nigeria Economic Summit Group and Heinrich Boll Stiftung on the true cost of electricity in terms of LCOE. It was reported by both bodies that right now, combined cycle turbines and large-scale natural gas generation are the most competitive electricity generation technologies in Nigeria (NESG and HBS, 2017). The higher LCOE cost for combined cycle turbines shows that it is advisable for power plants to operate gas turbines in combined cycle.

Society's Cost of Electricity for Climate Change Rate of USD40/tCO_2e

Table 5 shows the results of SCOE for the climate change rate of USD40/tCO_2e. It captured the costs associated with air pollution, levelized energy costs, system integration, climate change and SCOE gotten from additions of the considered costs. According to [22], determining the cost of power for the society is essential because it offers a more accurate estimation of the electricity producing methods that would most benefit Nigerian society both now and in the future.

Table 4: Levelized cost of energy

Location of power plants	Type of power plant	Daily Generation (MW)	Capacity cost (₦)	Capacity cost *CRF (₦)	FOM/8760* CF (₦)	Fuel cost*Heat Rate (₦)	VOM (₦)	LCOE (₦)
Ihovbor	OC	225	12,364,161,840.00	1,483,699,421.00	100,350.00	654,222,367.30	2,224,864,800.00	4,362,886,938.00
	CC	337.5	18,546,242,760.00	2,225,549,131.00	150,525.00	1,472,000,326.00	3,337,297,200.00	7,034,997,183.00
Omotosho NIPP	OC	250	18,046,489,539.00	2,165,578,745.00	111,500.00	783,643,782.10	2,472,072,000.00	5,421,406,027.00
	CC	375	27,069,734,308.00	3,248,368,117.00	167,250.00	1,763,198,510.00	3,708,108,000.00	8,719,841,877.00
Geregu NIPP	OC	290	15,936,018,789.00	1,912,322,255.00	129,340.00	1,059,091,893.00	2,867,603,520.00	5,839,147,008.00
	CC	435	23,904,028,184.00	2,868,483,382.00	194,010.00	2,382,956,759.00	4,301,405,280.00	9,553,039,431.00
Calabar NIPP	OC	450.4	24,750,285,734.00	2,970,034,288.00	200,878.40	2,554,667,668.00	4,453,684,915.00	9,978,587,749.00
	CC	675.6	37,125,428,600.00	4,455,051,432.00	301,317.60	5,748,002,253.00	6,680,527,373.00	16,883,882,375.00
Transcorp	OC	432	23,685,473,509.00	2,842,256,821.00	192,672.00	2,335,846,221.00	4,271,740,416.00	9,450,036,130.00
	CC	593.4	32,534,629,584.00	3,904,155,550.00	264,656.40	4,407,292,133.00	5867,710,099.00	14,179,422,439.00
Geregu Forte Oil	OC	290	15,899,970,643.00	1,907,996,477.00	129,340.00	1,059,091,893.00	2,867,603,520.00	5,834,821,230.00
	CC	435	23,849,955,964.00	2,861,994,716.00	194,010.00	2,382,956,759.00	4,301,405,280.00	9,546,550,765.00
Omotosho Pacific Energy	OC	228	14,809,717,975.00	1,777,166,157.00	101,688.00	603,235,154.00	2,254,529,664.00	4,635,032,663.00
	CC	342	22,214,576,963.00	2,665,749,236.00	152,532.00	1,357,279,096.00	3,381,794,496.00	7,404,975,360.00
Olorunsogo Pacific Energy	OC	228	12,529,007,876.00	1,503,480,945.00	101,688.00	651,219,768.50	2,254,529,664.00	4,409,332,066.00
	CC	342	18,793,511,814.00	2,255,221,418.00	152,532.00	1,465,244,479.00	3,381,794,496.00	7,102,412,925.00

Table 5: Society's cost of electricity for climate change rate of USD40/tCO_2e

Location of power plants	Type of power plant	LCOE	Cost of climate change (₦)	Cost of air pollution (₦)	System integration cost (₦)	SCOE (₦)	SCOE (₦/Kwh)	% Change in SCOE from OC to CC
Ihovbor	OC	4362886938	14,389,246,080.00	4,555,328,704.25	1,635,141,600.00	24,942,603,322.34	15.82	25.17
	CC	7034997183	14,081,454,720.00	4,428,885,278.91	2,452,712,400.00	27,998,049,581.52	11.84	
Omotosho NIPP	OC	5421406027	15,988,051,200.00	5,061,476,338.05	1,816,824,000.00	28,287,757,564.81	16.15	24.56
	CC	8719841877	15,646,060,800.00	4,920,983,643.23	2,725,236,000.00	32,012,122,319.94	12.18	
Geregu NIPP	OC	5839147008	18,546,139,392.00	5,871,312,552.14	2,107,515,840.00	32,364,114,791.85	15.92	24.67
	CC	9553039431	18,149,430,528.00	5,708,341,026.15	3,161,273,760.00	36,572,084,745.44	12.00	
Calabar NIPP	OC	9978587749	28,804,073,041.92	9,118,755,770.64	3,273,190,118.40	51,174,606,680.42	16.21	23.34
	CC	16883882375	28,187,943,137.28	8,865,644,131.64	4,909,785,177.60	58,847,254,821.59	12.43	
Transcorp	OC	9450036130	27,627,352,473.60	8,746,231,112.16	3,139,471,872.00	48,963,091,588.24	16.17	24.12
	CC	14179422439	24,758,326,609.92	7,786,964,517.05	4,312,413,446.40	51,037,127,012.36	12.27	
Geregu Forte Oil	OC	5834821230	18,546,139,392.00	5,871,312,552.14	2,107,515,840.00	32,359,789,014.26	15.92	24.67
	CC	9546550765	18,149,430,528.00	5,708,341,026.15	3,161,273,760.00	36,565,596,079.06	11.99	
Omotosho Pacific Energy	OC	4635032663	14,581,102,694.40	4,616,066,420.30	1,656,943,488.00	25,489,145,265.73	15.95	25.07
	CC	7404975360	14,269,207,449.60	4,487,937,082.62	2,485,415,232.00	28,647,535,124.24	11.95	
Olorunsogo Pacific Energy	OC	4409332066	14,581,102,694.40	4,616,066,420.30	1,656,943,488.00	25,263,444,668.29	15.81	25.20
	CC	7102412925	14,269,207,449.60	4,487,937,082.62	2,485,415,232.00	28,344,972,688.98	11.83	

Table 6: Society's cost of electricity for climate change rate of USD100/tCO_2e

Location of power plants	Type of power plant	LCOE (₦)	Cost of Climate Change (₦)	Cost of Air Pollution (₦)	System Integration Cost (₦)	SCOE (₦)	SCOE (₦/KWH)	% Change in SCOE from OC to CC
Ihovbor	OC	4,362,886,938.00	35,973,115,200.00	4,555,328,704.25	1,635,141,600.00	46,526,472,442.34	29.51	
	CC	7,034,997,183.00	35,203,636,800.00	4,428,885,278.91	2,452,712,400.00	49,120,231,661.52	20.77	29.62
Omotosho NIPP	OC	5,421,406,027.00	39,970,128,000.00	5,061,476,338.05	1,816,824,000.00	52,269,834,364.81	29.83	
	CC	8,719,841,877.00	39,115,152,000.00	4,920,983,643.23	2,725,236,000.00	55,481,213,519.94	21.11	29.24
Geregu NIPP	OC	5,839,147,008.00	46,365,348,480.00	5,871,312,552.14	2,107,515,840.00	60,183,323,879.85	29.61	
	CC	9,553,039,431.00	45,373,576,320.00	5,708,341,026.15	3,161,273,760.00	63,796,230,537.44	20.93	29.33
Calabar NIPP	OC	9,978,587,749.00	72,010,182,604.80	9,118,755,770.64	3,273,190,118.40	94,380,716,243.30	29.90	
	CC	16,883,882,375.00	70,469,857,843.20	8,865,644,131.64	4,909,785,177.60	101,129,169,527.51	21.36	28.57
Transcorp	OC	9,450,036,130.00	69,068,381,184.00	8,746,231,112.16	3,139,471,872.00	90,404,120,298.64	29.86	
	CC	14,179,422,439.00	61,895,816,524.80	7,786,964,517.05	4,312,413,446.40	88,174,616,927.24	21.20	28.99
Geregu Forte Oil	OC	5,834,821,230.00	46,365,348,480.00	5,871,312,552.14	2,107,515,840.00	60,178,998,102.26	29.61	
	CC	9,546,550,765.00	45,373,576,320.00	5,708,341,026.15	3,161,273,760.00	63,789,741,871.06	20.93	29.33
Omotosho Pacific Energy	OC	4,635,032,663.00	36,452,756,736.00	4,616,066,420.30	1,656,943,488.00	47,360,799,307.33	29.64	
	CC	7,404,975,360.00	35,673,018,624.00	4,487,937,082.62	2,485,415,232.00	50,051,346,298.64	20.88	29.55
Olorunsogo Pacific Energy	OC	4,409,332,066.00	36,452,756,736.00	4,616,066,420.30	1,656,943,488.00	47,135,098,709.89	29.50	
	CC	7,102,412,925.00.	35,673,018,624.00	4,487,937,082.62	2,485,415,232.00	49,748,783,863.38	20.76	29.64

For Ihovbor power plant, the results showed SCOE of 11.84 ₦/KWH and 15.82 ₦/KWH for combined cycle and open cycle, respectively. The Omotosho NIPP had a SCOE of 16.15 ₦/KWH and 12.18 ₦/KWH for open cycle and combined cycle turbines, respectively. The Olorunsogo Pacific Energy gave a lower SCOE for combined cycle compared to open cycle at a rate of 11.95 ₦/KWH and 11.83 ₦/KWH, respectively. In summary, for a climate change rate of USD40/tCO_2e, there is a change in the SCOE between the open cycle and combined cycle technology. These cost changes range between 23.34 % (as is the case with Calabar NIPP) and 25.20 % (as in the case of Olorunsogo Pacific). Therefore, it means that it costs less and is more beneficial to generate electricity without causing much harm to society.

Society's Cost of Electricity for Climate Change Rate of USD100/tCO_2e

Table 6 shows the society's cost of electricity for the climate change rate of USD100/tCO_2e. Stiglitz and Stern (2017) suggest that the figure of 100 USD/tCO_2e is a reasonable approximation to the current costs of climate change harm, as reported in international literature. This captures the levelized cost of energy, cost of climate change, cost of air pollution, system integration cost and society's cost of electricity, obtained from additions of the considered costs. Also, Table 6 depicts a similar pattern of results with the cost of climate change damage for 40USD/tCO_2e, where open cycle gas turbine has a lower society cost value in ₦/KWH than combined cycle gas turbines. Also, this reveals that the SCOE in ₦/KWH for Geregu Forte Oil is 29.61 ₦/KWH and 20.93 ₦/KWH in open and combined gas turbines, respectively. The SCOE for Calabar NIPP and Transcorp plant indicate 29.90 ₦/KWH and 21.36 ₦/KWH, 29.86 ₦/KWH and 21.20 ₦/KWH for both open and combined cycle gas turbines, respectively. In summary, for a climate change rate of USD100/tCO_2e, there is a change in the SCOE between the open cycle and combined cycle technology. These cost changes range between 28.57 % (as is the case with Calabar NIPP) and 29.64 % (as in the case of Olorunsogo Pacific).

CONCLUSION

This study evaluated the environmental and social benefits of converting Nigeria's electric power generating system from open cycle to mixed cycle gas power plants. It was observed that converting to combined cycle plant from the open cycle plant cost less and resulted in reduction of greenhouse gas based on international standard methods employed in this study. Also, it costs less to reduce air pollution damage during the process of conversion from open open-cycle gas plant to a combined cycle gas plant. The society's cost of electricity showed that it is more beneficial to generate electricity using a combined gas turbine. The society bears less cost for higher electricity generation by a combined cycle when compared with an open cycle. Based on the results, it is hereby proposed that the government support power plants in their efforts to reduce GHG emissions and the harm they cause to the environment by using combined cycle gas turbines to generate electricity. It costs less to reduce greenhouse gas and air pollution for a combined cycle than open open-cycle gas turbine.

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