



(RESEARCH ARTICLE)

Nigerian power sector: Why gas turbines will be relevant for the next 50 years

Ebigenibo Genuine Saturday * and Celestine Ebieto Ebieto

Department of Mechanical Engineering, University of Port Harcourt, PMB 5323, Choba, Port Harcourt, Nigeria.

Publication history: Received on 23 September 2020; revised on 13 October 2020; accepted on 18 October 2020

Article DOI: <https://doi.org/10.30574/gjeta.2020.5.1.0078>

Abstract

Several cases of the need for continuous utilization of gas turbines for power production and why gas turbines will be relevant in the next 50 years in the Nigerian power sector are presented in this paper. Using 7 criteria; the cost of installation, operation and maintenance costs, levelized cost of electricity, capacity factor, the efficiency of energy conversion, power to size ratio/area coverage and environmental pollution, gas turbine operation was compared with wind and solar energy technologies. Gas turbine for power production appears to be more favourable in 5 out of the 7 criteria including lower installation cost which is a very important factor for poor and developing nations like Nigeria. The quantity of fuel for producing different quantities of power using gas turbines was estimated. Nigeria has huge proven reserves of natural gas which is the fuel for gas turbines. If we go for combined cycle power plants which have low specific fuel consumption (SFC), 50% of the natural gas reserves are enough to produce some 35 GW of electricity for over 50 years. The current rate of natural gas production can produce 27.06 GW of electricity at 0.06kg/s.MW sfc. It was also observed that the current installed power from gas turbines is too low compared to the power demand; hence, further installations are required. Pollution should not be an issue in installing more gas turbine plants because the gas turbine is a clean-burning engine and the present installed capacity is insignificant compared to what is obtainable in some advanced nations. The results in this work will guide gas turbine operators in planning for further installation of gas turbine power plants. The study does not rule out the need to exploit solar photovoltaic system and wind turbines in areas with high sunshine and high wind speeds respectively, for off-grid power production.

Keywords: Capacity factor; Gas turbine; Specific fuel consumption; Wind turbines; Solar photovoltaic

1. Introduction

The Nigerian power sector is dominated by gas turbine power plants, constituting over 80% of the total grid-based installed capacity. This is followed by three hydropower plants. As of 2015, gas turbines constitute 85% of the total grid-based installed capacity while the three hydropower plants constitute 15% and the total installed capacity stood at 12,522 MW [1]. Before 2005, the power sector was solely under the control of the Nigerian government with Nigerian Electric Power Authority (NEPA) in charge of power production, transmission and distribution. The Nigerian government in 2005 came up with the Electric Power Sector Reform Act of 2005, which created the Power holding company of Nigeria (PHCN) to take the assets and liabilities of NEPA. The PHCN was later unbundled as part of the reforms to three distinct parts- power generating companies, the transmission company of Nigeria (TCN) and power distribution companies (DisCos). The reform also gave birth to a regulatory body, Nigerian electricity regulatory agency (NERC), rural electrification agency (REA), and rural electrification fund (REF). The REF is under the control of the REA for providing electricity to unserved and underserved areas far from the national grid through mini-grids [2]. The power generating companies consists of the traditional 6 generating companies (Gencos) that were owned by the federal government under PHCN before the unbundling (actually, there are 7 power plants but the hydro plants at Kainji and Jebba are combined to form Kainji/Jebba Hydro Electric Plc, with a total installed capacity of 1338 MW), all of which are privatized now, 8 independent power projects (IPP) which are all gas turbine-based power plants owned by state

* Corresponding author: Saturday Ebigenibo Genuine

Department of Mechanical Engineering, University of Port Harcourt, PMB 5323, Choba, Port Harcourt, Nigeria.

governments and independent bodies/organizations aside from the federal government and 10 National Integrated Power Projects (NIPP), all gas turbine-based power projects funded by the three tiers of government, managed by a private company incorporated by the federal government [3]. All the NIPP projects are meant to be privatized. The 11 DisCos which are privately owned handle power distribution while power transmission is still left with the federal government.

The reforms were aimed at improving power production with room for private investment in power generation and distribution for grid-based power. It also creates room for private investors to provide power to communities and businesses far from the national grid or underserved areas through mini-grids [4]. While newly registered mini-grids are usually renewable energy-based, all the IPPs connected to the national grid are gas turbine-based. Several other IPPs exist which are not connected to the national grid. New IPPs could be based on wind energy or solar energy or even hybrid systems. It is pertinent to note that the electricity tariffs from the mini-grids are usually much higher than the grid-based electricity in Nigeria. Despite the reforms in the sector with private investors' inclusion, the total installed capacity is far less than the electricity demand.

Many rural populations have no access to the national grid. The mini-grids are slowly coming up and have very low coverage compared to areas connected by the national grid. As electricity supply is insufficient, the Nigerian government saw the need to supply electricity to business clusters through the Energizing Economies Initiative (EEI) in 2017 under the REA. Off-grid electricity with over 70% renewable energy-based is meant to furnish over 100,000 business clusters. It is part of the nation's Micro, Small, Medium Enterprise (MSMEs) programme aimed at promoting economic growth [5]. Solar photovoltaic (PV) system is used in several areas where the programme has taken off. Aside from the EEI programme, the Nigerian government has also launched the Energizing Education Programme (EEP) [6]. This is another initiative of the federal government aimed at providing clean and sustainable power for the 37 federal universities and 7 teaching hospitals across the nation. The programme is in phases and while some projects in phase I are completed those in phase II have been identified [7]. While solar hybrid systems are suitable for the EEP in some states in the northern part of Nigeria, Many states around the Niger Delta region can employ gas turbines for continuous and sustainable power supply. NERC [8] provided 7 opportunities in power generation some of which are off-grid. Gas turbines can effectively feature in each of the generation options, although much attention may be geared towards renewable energy.

All the mini-grids operational today are isolated and serve only unserved areas. When the grid extends to their areas of operation, is either they sell their assets to the DisCos or operate as interconnected mini-grids with power purchase agreements. Mini-grid operators are afraid of this occurrence in the future and likely political inference and tend to operate with proper protection from the state governments in the areas they operate now. As at today, they charge higher but are able to operate economically viable due to available subsidies. Is that the way to go? The government ought to make money from electricity production and not to pay subsidy in providing electricity to its citizenry.

The national grid wheeling capacity is less than 10,000 MW, although this value was targeted by July 2020 from a possible exiting value of 8100 MW, while 20,000 MW was targeted in 2022. NERC [9] reported a theoretical transmission wheeling capacity of 7500 MW in the past. This implies that if all grid-connected plants and other IPPs meant to be connected to the grid are fully operational, the total power generated cannot be evacuated. The opportunities for power generation involving off-grid appears as a solution or a way out to provide power to remote areas and business clusters as planned. The big question is- which is more cost-effective- extending the grid to areas not covered and employing off-grid solution? In the real sense, off-grid comes to bear because of the inability of the operators to extend the national grid to all areas and generate enough power to serve the entire nation. With the present situation we find ourselves, off-grid power generation cannot be discouraged. But in doing so, can we rule out gas turbines in the picture? Can solar and wind energy sources provide the needed off-grid power solution completely in all parts of Nigeria? A peep into the quantities of the different renewable energy sources in Nigeria is necessary.

2. Renewable energy potentials in Nigeria

Several works have been carried out to assess renewable energy potentials in different parts of Nigeria. For the sake of off-grid power production, the major renewable energy sources that will come to mind are solar PV and wind energy systems. Bio-fuels (from biomass) if exploited are meant to run steam plants or gas turbine engines, but with far lower calorific values, may not be too attractive compared to natural gas. But, they cannot be ruled out as they are renewable and more environmental friendly in combustion. Small hydro can be easily exploited off-grid while large hydro is exploited in Nigeria and connected to the national grid. Other renewable energy systems available are solar thermal, tidal energy, wave energy, geothermal energy, and hydrogen.

In the renewable energy master plan (REMP), the potentials of large scale hydropower are estimated as 10,000 MW, small scale hydropower as 734 MW, solar radiation in the range 3.5-7.0kWh/m²-day, and average annual wind speed in the range 2- 4 m/s [10]. These are estimated values from a single source; values from other sources may be slightly different. Wind speed values are usually expressed at a particular height. Average wind speed values greater than 4 m/s at 10 m height are obtained in several locations in Nigeria. Although higher wind speeds are recorded in the Northern part of Nigeria, wind speeds along the coastal regions of the southern part are quite high. The wind speeds are generally on the low side in several locations in Nigeria. Large and small scale hydropower potentials are put at 11,250 MW and 3500 MW respectively while wind speed is put at 2-9 m/s at 10 m height in Akorede et al. [11].

There are several works on renewable energy potentials/utilization in Nigeria. Some deal with small hydropower utilization [12, 13], some on wind energy potentials [14, 15], and some on solar energy utilization [16, 17] while others considered several renewable energy systems [18-21]. The renewable energy potentials for the given study areas are provided in these works and the amount of electricity that can be generated is often estimated. Aside from large hydro, the other renewable energy potentials such as wind energy and solar energy can be easily harnessed for electricity generation off-grid. They can thus serve particular localities. Areas with high solar radiation can go for solar PV systems for electricity generation while those with high wind speeds can go for wind turbines for electricity generation. The utilization of these systems can be in modular form but the smaller the capacity the higher the installation cost per power output. The modularity makes it easier to add additional power to the existing installations compared to large hydropower plants and conventional thermal power systems. The studies reviewed show that renewable energy potentials can be utilized to meet the power demand in Nigeria. Although, the studies hardly considered the economic implications of installing renewable energy systems to meet our electricity needs compared to conventional power generation technologies in Nigeria, especially, the gas turbine power plants.

3. Conventional power installations versus renewable energy systems

The two basic conventional electricity generation systems for grid-connected power in Nigeria are gas turbine power plants and large hydropower plants. The hydropower plant is renewable, hence, it is not considered in this comparison. Gas turbine power plants can thus be compared with wind turbine systems and/or solar photovoltaic systems. To do this comparison, the following questions should be answered: "Why has Nigeria not being able to provide electricity for her populace with the conventional power installations?" Is it because the conventional power installations are too costly to install, too costly to operate/maintain, has a low capacity factor, inefficient to operate, too cumbersome to maintain, and/or affects the environment too adversely hence neglected by the operators? How does the capacity of gas turbine installations in Nigeria compare with those of some advanced countries is another question we need to ask if we consider environmental pollution from gas turbines.

3.1.1. Cost of installation

The installation cost of power systems varies with capacity, equipment manufacturers, and location of the power plant. For onshore wind energy system, the installation cost is in the range \$1,200 per kW to \$1,600 per kW, the value for offshore wind energy systems is much higher and in the range \$2,700 per kW to \$5,300 per kW [22]. The installation cost of fixed-tilt utility-scale solar PV systems is \$1.44/W (\$1440/kW). The values for residential and commercial-scale systems are much higher (\$3110/kW and \$2100/kW respectively) [23]. Unfortunately, most of the solar PV systems in use so far in Nigeria fall into the residential category but the installation cost is much lower than \$3100/kW. The installation cost of a gas turbine power plant depends on the configuration. For the open cycle plant, the installation cost of \$860/kW has been reported for a 580 MW plant [24]. Lower installation costs have been reported by other sources. Gas turbine power plants have lower installation costs today compared to wind and solar PV systems, although, the installation costs of the later systems have been declining. For a given power demand, the amount of power to be installed depends on the capacity factor of the power generation system. Capacity factor is considered later.

3.1.2. Operation and maintenance costs

The operation and maintenance (O&M) cost of wind and solar energy systems are very low compared to that of gas turbine power plants. The O&M cost of wind energy systems in Europe are in the range 1.2 to 1.5 Eurocents per kWh (\$14.22 to \$17.77 per MWh) [25], while that of a solar PV system is even lower with a value of \$13/ KW-yr (\$1.454/ kWh) [23]. Much lower values in the range \$4/ KW-yr - \$9.5/ KW-yr (\$0.46/ MWh - \$1.08/ MWh) for solar PV system has been recorded [26]. If operating in Nigeria, the O&M cost values for both wind energy and solar PV systems will be lower than those cited here because labour / administrative costs which form a good percentage of the O&M cost is very low in Nigeria.

For a gas turbine, the fuel cost may be taken as part of the O&M cost. The fuel (natural gas) cost is high and constitutes the major part of the O&M cost. The cost of natural gas is either expressed in monetary value per power output (e.g \$/kWh) or monetary value per mass or volume (e.g, \$/ft³). The former expression is typical to the power industry and it is disadvantageous to the gas producers- the inefficiencies of the engine operators are borne by the gas producers as the engine operators pay for natural gas per power output. Engine operators buy gas from the gas operator in US dollar but at prices lower than the global values. In January 2020 and May 2020, the price of natural gas per thousand cubic foot was 3.66 and 2.87 respectively [27]. The price of natural gas in the Nigerian power sector should be much lower and should not be influenced by global prices. For a 26MW gas turbine power plant with a fuel flow rate of 1.98 kg/s, taking the density of natural gas as 0.8 kg/m³, the fuel cost per second for the natural gas price of \$2.5 per thousand cubic foot will be \$0.1398 (₦50.48). In one hour, the fuel cost will be \$503.45, and the power produced will be 26 MWh. Thus, the fuel cost in terms of power produced is \$ 19.36/MWh. If the fuel cost is taken as 70% of the total O&M cost, the total O&M cost will be \$27.66/MWh. This value is lower than an average value of \$34/MWh quoted in [22]. For bigger gas turbine engines, the fuel consumption per power output will be lower, meaning lower O&M cost values. The O&M cost of the gas turbine system though comparatively much higher, but economically a viable system to operate, knowing that average electricity prices of ₦35/kWh and ₦42/kWh are equivalent to \$96.95/MWh and \$116.34/MWh respectively.

3.1.3. Levelized cost of electricity

Aside from the installation and O&M costs, the levelized cost of electricity (LCOE) which is the ratio of the total life cycle cost of electricity production to the total electricity production is another cost parameter for assessing the economic viability of power plants. A lot of assumptions are made in the calculation of LCOE. At high discount rates, plants with high installation costs go with high LCOE values. Often, very low discount rates (much lower than bank lending rates in Nigeria) are used in calculating LCOE. At such low discount rates, the LCOE from wind and solar energy systems are comparable to those from gas turbine systems. The LCOE from gas turbine systems are usually lower at discount rates similar to bank lending rates in Nigeria.

3.1.4. Capacity factor

Capacity factor refers to the average amount of power recorded from a power generating system over a given time to the theoretical maximum power output from the system. This can be expressed mathematically as,

$$CF = \frac{P_{av}}{P_{max}} \quad (1)$$

Where CF , P_{av} and P_{max} represent capacity factor, average power produced, and theoretical maximum power produced respectively. For any given power generation system, the average power produced should at least be equal to the power demand. This implies that the amount of power to be installed should be greater than the power demand and the two parameters are connected by the capacity factor in the form,

$$P_{int} = \frac{P_D}{CF} \quad (2)$$

Where P_{int} and P_D are the power installed and power demand respectively. A power system with low capacity factor will have to install more power to meet the power demand and vice-versa. Renewable energy systems are intermittent and thus go with low capacity factors. This is the major (if not the only) disadvantage of renewable energy systems. The capacity factor of the wind energy system is usually higher than solar PV plants as the latter requires sunlight to operate. For wind energy systems, capacity factor above 0.6 can be obtained while that of solar PV is usually below 0.35 [28]. For gas turbines operated for baseload as in Nigeria, the plants can run for several days without being shut down. The power produced is at the off-design condition and hence lower than the value provided by the manufacturers which are at the international organization for standardization (ISO) condition. If the capacity factor is calculated with respect to maximum possible field power output, values greater than 0.9 will be obtained for most gas turbines. In the present scenario, there are cases of forced shutdowns due to 'shortage of natural gas' resulting from vandalization and other avoidable causes. This makes the capacity factor of gas turbine power plants operating for baseload in Nigeria to be lower than 0.9. Although the installation costs of solar and wind energy systems are decreasing with technology spread, they have lower capacity factors and larger installations are required to meet the power demand compared to gas turbines.

3.1.5. Efficiency of energy conversion

Solar PV systems have conversion efficiencies in the range of 15% to 20%. For wind energy systems, the efficiency is limited by Betz limit which is $16/27$ (59.26%). For simple cycle gas turbine power plants, thermal efficiency up to 40% can be achieved in some plants. Much higher thermal efficiencies can be obtained for combined cycle plants, as much as 60%. It is pertinent to point out that while Olorunsogo II Power Plant in Ogun State in the NIPP is a combined cycle power plant, many others are simple cycle plants with provision for expansion and conversion to combined cycle power plants in the future. Whether that future will ever come is not known to anybody today, but it is feasible. Even if the conversion efficiency of any renewable energy conversion system is adjudged to be low, the energy resource is not depleting, the same cannot be said of conventional fossil-fuel-powered systems. Thus gas turbine plants ought to go with higher conversion efficiencies.

3.1.6. Power to size ratio / area coverage

Both wind turbine and solar PV systems require large area per power output for operation. The area per unit power for solar PV system depends on the yield or efficiency of the solar panels. The greater the efficiency of the solar panels the smaller the area per unit power and vice-versa. To produce 1MW of electricity, 4 acres ($4 \times 4046.86 \text{ m}^2$) are required when crystalline solar panels are used without trackers while thin-film solar panels without trackers require 6 acres ($6 \times 4046.86 \text{ m}^2$). A thermal power plant such as gas thermal power plant of 100 MW will require less than 10% of the area required by a solar PV plant of the same capacity [29]. Wind turbines are installed in open spaces far away from obstructions. Offshore wind turbines have the advantage of vast unrestricted space. For onshore wind turbines, the area depends on the wind speed and the size of the turbine blades. Higher wind speed together with higher blade diameters goes with higher turbine power output and hence fewer installations. But large blade diameters also imply large area coverage. Also, much space is required between the turbines to curtail turbulence. About one square kilometre ($1000000 \text{ m}^2 = 247.105 \text{ acres}$) is required to produce 4 MW of electricity from wind turbines [30]. This is equivalent to 61.78 acres per MW. Compared to thin-film solar PV system without trackers, wind turbines require more than 10 times the area required by the solar PV system. Gas turbines have the advantage of smaller area per power output not only in comparison with solar and wind energy technologies but also in comparison with other internal combustion engines.

3.1.7. Environmental pollution

Renewable energy systems such as solar and wind energy systems do not pollute the environment with emissions as internal combustion engines such as gas turbines and diesel engines do. But these renewable energy technologies require energy storage system in the form of batteries due to the intermittent nature of the energy resources. Battery life varies between 5 and 15 years. When the batteries are non-functional they have to be recycled, especially lead-acid batteries by going back to the manufacturers. This implies non-functional lead-acid batteries have a positive residual value and the owners make some money in returning them to the manufacturers. The same cannot be said of lithium-ion batteries which residual value is less than the cost of processing in recycling [31]. A large bank of batteries will be required for solar PV projects to power a whole state like Kano with a high population and high average annual solar radiation. Knowing that the batteries are largely imported, there is a need to set up recycling centres in Nigeria ahead of time, otherwise, they will constitute a nuisance to the environment which we intend to protect from pollution.

Gas turbine appears to be the cleanest burning engine among all the internal combustion engines that run on fossil fuels. Even with the minimal emissions from gas turbines, caution must be taken to ensure the entire power demand of Nigeria is not met with power from gas turbine power stations only. The Energy Commission of Nigeria (ECN) estimated the power demand of Nigeria as between 45.49 GW and 88.282 GW in 2020 for different GDP growth rates between 7% and 13% with 2009 as the base year [32]. Knowing that Nigeria has not gotten up to 7% GDP growth rate since 2011, the 45.49 GW energy demand projection is still on the high side. A much lower energy demand value of 16.774 GW in 2020 was estimated by Ezennaya et al. [33]. Presently, the total grid-connected power from gas turbines is put at 10.592 GW out of which the actual power available for use is less than 4.0 GW. This is far less than even the 16.774 GW energy demand projection. Compared to some other nations, Japan has over 76 GW installed power from gas turbines in addition to several other sources of power, China has relatively low gas turbine installations with over 21 GW installed power, but it has over 160 GW of installed power from coal-fired plants which have far more pollution issues compared to gas turbines. India, like China, has a relatively low capacity of gas turbine installations (some 24 GW) but with over 159 GW from coal-fired plants while the USA has gas power plants with an installed capacity of over 380 GW [34] (more than 35 times that of Nigeria). Thus, with a paltry installed capacity of little above 10 GW from gas turbines, pollutions from gas turbines should not be an issue in Nigeria. Besides, carbon capture technology has been employed in gas turbine and coal-fired steam turbine power plants to curtail pollutions.

3.2. Natural gas deposits in Nigeria and derivable electrical power

Gas turbines are fired by natural gas. Nigeria has some 5761 billion cubic metre of proven natural gas reserves as of 2019 [35]. Here, the electrical power that can be derived from say 50% of the natural gas reserves will be estimated. Half of the reserves will be used because the reserves are only estimates. Also, there are other uses of natural gas including domestic use and majorly exports. In terms of mass, the natural gas deposits are,

$$R_{NG,m} = \rho_{NG} \times R_{NG,V} \quad (3)$$

Where $R_{NG,m}$, $R_{NG,V}$ and ρ_{NG} are the natural gas reserves in mass, natural gas reserve in volume, and density of natural gas respectively. The density of natural gas is taken as 0.8 kg/m³ in this work. The time (in years) to deplete 50% of the reserves for electric power production depends on the amount of the reserves, the specific fuel consumption (sfc) and the amount of power to be produced. This is given by Equation (4),

$$t = \frac{0.5 \times R_{NG,m}}{sfc \times P_{out} \times (365 \times 24 \times 60 \times 60)} \quad (4)$$

Where P_{out} is the amount of power to be produced in MW. The value of the specific fuel consumption of a gas turbine plant is around 0.05 - 0.07 kg/s per MW, with the value decreasing with an increase in capacity of the gas turbine engine. For combined cycle power plants, the sfc will be lower. Tables 1 to 4 show the time required to deplete 50% of the reserves for different quantities of power generation for sfc of 0.04, 0.05, 0.06 and 0.07 respectively. To produce a specified amount of power output at a given sfc, the amount of natural gas to be utilized daily need to be estimated. This is to give the gas turbine operators and the gas producers the quantity of gas to be produced to meet the power need per day. The mass of natural gas (m_{NG} in kg) required per day is given by Equation (5),

$$m_{NG} = P_{out} \times sfc \times (24 \times 60 \times 60) \quad (5)$$

In the industry, the quantity of natural gas is usually expressed in volume, either in billion standard cubic foot per day (bscfd), in million cubic foot or in million cubic metre. Equations (6) and (7) give the volume of natural gas required per day in million cubic metre and million cubic foot respectively,

$$V_{NG,SI} = \frac{m_{NG}}{\rho_{NG}} \times 10^{-6} \quad (6)$$

$$V_{NG,CF} = V_{NG,SI} \times 35.3147 \quad (7)$$

Where $V_{NG,SI}$ is the volume of natural gas required per day in million cubic metre and $V_{NG,CF}$ is the volume of natural gas in million cubic foot. Table 5 shows the quantity of natural gas required per day for different values of power output for sfc of 0.06.

Table 1 Time to deplete reserves by 50% for different power outputs for sfc of 0.04 kg/s.MW

Power output, MW	10	15	20	25	30	35	40	45	50
Time, yrs	182.68	121.79	91.34	73.07	60.89	52.19	45.67	40.60	36.54

Table 2 Time to deplete reserves by 50% for different power outputs for sfc of 0.05 kg/s.MW

Power output, GW	10	15	20	25	30	35	40	45	50
Time, yrs	146.14	97.43	73.07	58.46	48.71	41.76	36.54	32.48	29.23

Table 3 Time to deplete reserves by 50% for different power outputs for sfc of 0.06 kg/s.MW

Power output, GW	10	15	20	25	30	35	40	45	50
Time, yrs	121.79	81.19	60.89	48.71	40.60	34.80	30.45	27.06	24.36

Table 4 Time to deplete reserves by 50% for different power outputs for sfc of 0.07 kg/s.MW

Power output, GW	10	15	20	25	30	35	40	45	50
Time, yrs	104.39	69.59	52.19	41.76	34.80	29.83	26.10	23.20	20.88

Table 5 Quantity of natural gas required per day for different values of power output for sfc of 0.06

Power output, GW	Mass, million kg	Volume	
		million cubic metre	million cubic foot
10	51.84	64.80	2288.39
15	77.76	97.20	3432.59
20	103.68	129.60	4576.79
25	129.60	162.00	5720.98
30	155.52	194.40	6865.18
35	181.44	226.80	8009.37
40	207.36	259.20	9153.57
45	233.28	291.60	10297.77
50	259.20	324.00	11441.96

From Table 1, the number of years required to deplete the reserves decreases with the power output. The sfc here is 0.04 kg/s.MW. This low sfc can be obtained in combined cycle power plants. Thus, if we go with combined cycle power plants, we can produce 35 GW of electricity, which may be higher than the actual power demand of Nigeria today, for over 50 years. The time to deplete the reserves at a given power output decreases with an increase in sfc as observed from Tables 1 to 4. For sfc of 0.07 kg/s.MW which is obtainable in small open cycle gas turbine engines, to produce 20 GW of electricity will require less than 53 years to deplete half of the reserves; for sfc of 0.04, the value is as high as 91 years. This implies the need to go for combined cycle power plants as against simple cycle plants. The results above are for only 50% of the gas reserves. With Nigeria's power demand estimated in some quarters to be below 20 GW today, gas turbines can be employed solely to meet the energy demand of Nigeria for the next couple of years and some 35 GW of electricity can be produced continuously from gas turbines for over 50 years with combined-cycle configuration.

The quantity of natural gas to be used for different values of power to be generated is shown in Table 5. To generate 30 GW of electricity, 194.40 million cubic metre of natural gas is required per day. There is a need to compare the amount of natural gas production in Nigeria with the amount of natural gas required to power gas turbines to meet the power demand.

3.2.1. Comparison of natural gas production with the quantity required for power plants

Nigeria exported 35953.1 million cubic metres of natural gas in 2019 [35]. This translates to average daily export of 98.502 million cubic metre. From the Nigerian government's baseline report on power [1], 41% of the natural gas produced is exported while 27% is re-injected with only 9 % used to power the gas turbines. Using these values, the

total daily natural gas production excluding the 27% re-injected is 175.38 million cubic metre. If 9% of this value (15.784 million cubic metre) is used for power generation, only about 2.44 GW of electricity could be generated for sfc of 0.06 kg/s.MW while up to 3.65 GW of electricity could be generated if sfc is 0.04 kg/s.MW. The baseline report gave about 0.8 bscfd (22.653 million cubic metre) as the quantity of natural gas for power generation in Nigeria. This value will produce about 3.49 GW of electricity for sfc of 0.06 kg/s.MW. If the demand for power in Nigeria today is 30 GW, from Table 5, this will require 194.40 million cubic metre of natural gas which is above the average daily production of 175.381 million cubic metre in 2019. The total average daily production could power gas turbines to generate about 27.06 GW of electricity for sfc of 0.06. Fuel should not be a limitation to gas turbines usage in Nigeria. Gas turbines can be fired with biogas, although biogas has lower calorific value compared to natural gas. Now that we have abundant reserves of natural gas, there is a need to flood the power industry with gas turbines for as long as the reserves will serve us.

4. Conclusion

This paper made several cases for the need for the continuous use of gas turbines for power production in Nigeria. Gas turbines run on natural gas and because of environmental pollution issues from fossil fuel-fired plants, there are efforts to invest in renewable energy technologies for power production. In doing so, gas turbines should not be done away with for power production because it is the cleanest burning engine with low emissions. A comparison was made between two renewable energy technologies- solar PV system and wind turbine power plants with gas turbine power plants on the basis of cost of installation, operation and maintenance costs, levelized cost of electricity, capacity factor, the efficiency of energy conversion, the power to size ratio/area coverage and environmental pollution. Wind and solar energy technologies are only preferable to gas turbines on operation and maintenance cost and environmental pollution while gas turbine operation is better in the other five criteria. On pollution, the total installed gas turbine capacity is very small and issues of pollution should not deter us from further investment in gas turbine power plants as the total installed capacity is far lower than what is obtained in several advanced nations.

In Nigeria today, the power supply is lower than the demand. This is because the total installed power is lower than the demand, and existing plants are operating at lower capacities due to the non-availability of gas and breakdowns for gas turbines. More gas turbine power stations are needed because we have enough gas reserves to power gas turbines and gas turbine burns very clean. Good enough, the renewable energy master plan observed the need for gas for production in moving away from oil in the future. Also, gas turbines can be operated off-grid and features in all the opportunities identified in the power generation sector. Despite the advantages of gas turbines, there is a need for a broad electricity mix. Some states in Northern Nigeria with high annual solar radiation should engage solar power plants, for now, solar PV (as concentrated solar power plants are relatively less utilized due to very low efficiency and higher installation cost), while those areas with high wind speeds, more than 5 m/s can go for wind turbines. This study did not only make valid cases for the continuous utilization of gas turbines for electricity production in Nigeria amidst renewable energy technologies, but it also revealed the level of production of natural gas to meet different power requirements. The results will guide gas turbine operators in planning for further installation of gas turbine power plants to meet the electricity demand in Nigeria.

Compliance with ethical standards

Acknowledgments

The authors expressed their profound grateful to the department of mechanical engineering, university of Port Harcourt for providing conducive environment for this research.

Disclosure of conflict of interest

This work was not sponsored by any organization or agency. The work was carried out and sponsored by the authors, and there is no conflict of interest of any sort from any quarters.

References

- [1] Federal Government of Nigeria (FGN). Nigeria power baseline report, 2017 [cited 2020 August 07]. Available from <https://mypower.ng/wp-content/uploads/2018/01/Baseline-Report.pdf>.
- [2] FGN. Electric power sector reform act, 2005 [cited 2020 August 07]. Available from <https://www.power.gov.ng/download/Electric%20Power%20Sector%20Reform%20Act%202005.pdf>.

- [3] Niger Delta Power Holding Company [Internet]. [cited 2020 August 07]. Available from <http://www.ndphc.net/index>.
- [4] World Bank. Mini grids in Nigeria: a case study of a promising market, 2017 [cited 2020 August 07]. Available from <http://documents1.worldbank.org/curated/en/352561512394263590/pdf/ESM-dNigeriaMiniGridsCaseStudyConfEd-PUBLIC.pdf>.
- [5] Rural Electrification Agency, Energizing economies initiative, 2017[cited 2020 August 09]. Available from <https://rea.gov.ng/energizing-economies/>.
- [6] Energizing Education Programme [Internet]. [cited 2020 August 09]. Available from <https://rea.gov.ng/energizing-education-programme-2>.
- [7] FGN. Fact sheet on energizing education programme, 2018 [cited 2020 August 11]. Available from <https://www.yemiosinbajo.ng/fact-sheet-on-energizing-education-programme>.
- [8] NERC. Power generation in Nigeria, 2202 [cited 2020 August 12]. Available from <https://nerc.gov.ng/index.php/home/nesi/403-generation#>.
- [9] NERC. Transmission, 2020 [cited 2020 August 12]. Available from <https://nerc.gov.ng/index.php/home/nesi/404-transmission>.
- [10] Energy Commission of Nigeria, Renewable energy master plan, 2005 [cited 2020 August 12]. Available from: <http://www.greenplanetinitiative.org/wp-content/uploads/2016/09/REMP20Final20Report.pdf>
- [11] Akorede MF, Ibrahim O, Amuda SA, Otuoze AO, Olufeagba BJ. Current status and outlook of renewable energy development in Nigeria, *Niger. J. Technol.* 2017; 36: 196–212.
- [12] Ohunakin OS, Ojolo SJ, Ajayi OO. Small hydropower (SHP) development in Nigeria: an assessment. *Renewable and Sustainable Energy Reviews.* 2011; 15(4): 2006–2013.
- [13] Adejumobi, I.A., Adebisi, O.I., Oyejide, S.A. 2013 Developing small hydropower potentials for rural electrification. *International Journal Recent Research Applied Studies*, 17(1), 105–110.
- [14] Oyedepo SO, Adaramola MS, Paul SS. Analysis of wind speed data and wind energy potential in three selected locations in South-East Nigeria, *Int. J. Energy Environ. Eng.* 2012; 3: 1–11.
- [15] Akpinar EK, Akpinar S. An assessment on seasonal analysis of wind energy characteristics and wind turbine characteristics, *Energy Convers. Manag.* 2005; 46:1848–1867.
- [16] Dioha MO, Kumar A. Rooftop solar PV for urban residential buildings of Nigeria: A preliminary attempt towards potential estimation, *AIMS Energy.* 2018; 6: 710–734.
- [17] Oji JO, Idusuyi N, Aliu TO, Petinrin MO, Odejobi OA, Adetunji AR. Utilization of solar energy for power generation in Nigeria, *Int. J. Energy Eng.* 2012; 2(2): 54–59.
- [18] Bamisile O, Dagbasi M, Babatunde A, Ayodele O. A review of renewable energy potential in Nigeria; solar power development over the years, *Eng. Appl. Sci. Res.* 2017; 44(4): 242–248.
- [19] Shaaban M, Petinrin JO. Renewable energy potentials in Nigeria: meeting rural energy needs, *Renew. Sustain. Energy Rev.* 2014; 29: 72–84.
- [20] Emodi VN, Yusuf SD, Boo KJ. The necessity of the development of standards for renewable energy technologies in Nigeria, *Smart Grid Renew. Energy.* 2014; 5: 259–274.
- [21] Oyedepo SO. Towards achieving energy for sustainable development in Nigeria, *Renew. Sustain. Energy Rev.* 2014; 34: 255–272.
- [22] Wind Power Monthly [Internet]. Energy cost analysis 2020: Wind is ready for zero-subsidy future, [cited 2020 August 15]. Available from <https://www.windpowermonthly.com/article/1671659/energy-cost-analysis-2020-wind-ready-zero-subsidy-future>.
- [23] Fu R, Feldman D, Margolis R. US solar photovoltaic system cost benchmark : Q1 2018, NREL, 2018 [cited 2020 August 15]. Available from <https://www.nrel.gov/docs/fy19osti/72399.pdf>.
- [24] Pauschert D. Study of equipment prices in the power sector, ESMAP Technical Paper 112/09, Washington, D.C. 2008 [cited 2020 August 15]. Available from https://esmap.org/sites/default/files/esmap-files/TR122-09_GBL_Study_of_Equipment_Prices_in_the_Power_Sector.pdf. Accessed 11/08/2020.

- [25] Wind Energy-The Facts [Internet]. Operation and Maintenance costs of wind generated power, [cited 2020 August 21]. Available from <https://www.wind-energy-the-facts.org/operation-and-maintenance-costs-of-wind-generated-power.html>, .
- [26] PV Magazine [Internet]. How solar power operations and maintenance costs fell 50%, [cited 2020 August 21]. Available from <https://pv-magazine-usa.com/2019/09/13/how-solar-power-operations-and-maintenance-costs-fell-50-percent/>.
- [27] US Energy Information Administration [Internet]. Natural gas, [cited 2020 August 21]. Available from <https://www.eia.gov/dnav/ng/hist/n3035us3m.htm>.
- [28] US Energy Information Administration [Internet]. Electric power monthly, [cited 2020 August 21]. Available from https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b.
- [29] Suncyclopedia [Internet]. Solar power plants, [cited 2020 August 22]. Available from <http://www.suncyclopedia.com/en/area-required-for-solar-pv-power-plants/>.
- [30] Sciencing [Internet]. How much land is needed for wind turbines, [cited 2020 August 22]. Available from <https://sciencing.com/places-wind-turbines-produce-electricity-5159049.html>.
- [31] Solar Power World [Internet]. The importance of recycling batteries on solar projects, [cited 2020 August 24]. Available from <https://www.solarpowerworldonline.com/2019/10/a-qa-on-battery-recycling/>.
- [32] Energy Commission of Nigeria. National energy masterplan, 2014 [cited 2020 August 24]. Available from [https://www.energy.gov.ng/Energy_Policies_Plan/Draft%20\(Reviewed\)%20NEMP%20-%202014.pdf](https://www.energy.gov.ng/Energy_Policies_Plan/Draft%20(Reviewed)%20NEMP%20-%202014.pdf).
- [33] Ezennaya OS, Isaac OE, Okolie UO, Ezeanyim OIC. Analysis of Nigeria's national electricity demand forecast (2013-2030), International Journal of Scientific & Technology Research, 2014; (3(3): 333-340.
- [34] Global Energy Observation [Internet]. Current list of gas power plants, [cited 2020 August 24]. Available from <http://globalenergyobservatory.org/list.php?db=PowerPlants&type=Gas>.
- [35] Organization of Oil Exporting Countries (OPEC) [Internet]. Nigeria facts and figures, [cited 2020 August 25] Available from https://www.opec.org/opec_web/en/about_us/167.htm.