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TECHNO-ECONOMIC ASSESSMENT OF MUNICIPAL NATURAL GAS-POWERED (OFF-GRID) ALTERNATIVE ELECTRIC POWER SUPPLY IN LAGOS STATE, NIGERIA

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ABSTRACT

This study examined the techno-economic viability of natural gas-powered (off-grid) alternative electric-power infrastructure for municipalities in Lagos State, Nigeria as a strategic model for regional/national power infrastructure development. Techno-economic data were obtained through literature, questionnaire and site inspection. An energy project foresight analysis framework was used. The study determined appropriate power-plant locations at Apapa, Ikeja and Festac-Town Divisions of Lagos State. Technical/economic requirements per power plant included a 15-MW power-plant design over 5.145 acres, annual natural-gas requirements of approximately 160 million scf, and investments of ₦ 5.2 – 6.7 billion. Profitability Indices include Net Present Values of ₦ 107.63 – 1,636.93 million, 1-year break-even time per location, and payback period of 12 – 20 years. Techno-economic benefits/location/annum were 46,720 MWh of electricity, fuel-cost savings of ₦ 765.7 million, and CO_2 emissions savings of 3.45 Metric Kilotonnes. The study concluded that the infrastructure was techno-economically viable, and a suitable template for Nigeria.

Keywords: *Natural-gas power plants; Lagos Power Infrastructure; Energy planning; Project foresight analysis; Critical power infrastructure; Electric power supply; Off-grid electric power systems.*

1. INTRODUCTION

Power generation systems are critical infrastructure imperative for the socio-economic and technological development of nations; and access to modern electric power services is indispensable to the national provision of reliable, cost-effective residential, industrial and commercial services such as lighting, entertainment, food production, healthcare, transport and telecommunication (Momodu *et al.*, 2011; OECD, 2011; Jesuleye *et al.*, 2012; Ajayi *et al.*, 2014; Ogundari *et al.*, 2017; Taylor, 2017). Global electricity generation highlights natural gas as the second largest power generation fuel source at 21% of supply; while, on in individual country basis, natural gas is either number one, or in the top four (EIA, 2020; WEC, 2020). Global investment in natural gas as an electricity power source is on the rise, with many countries in Europe, Asia and the Americas incorporating off-grid systems for sustainable electricity generation (EIA, 2020; WEC, 2020).

In Nigeria, about 80% of national power generation infrastructure is gas-powered thermal plants; and natural gas (national estimated reserves: 5.2 trillion cubic metres) is a critical input to national energy security (PwC, 2016; FGN, 2018). Inexplicably Nigeria, despite being energy resource-rich, exhibits a national electric power system in disarray – there are wide and daunting electricity demand and supply gaps, and recurrent power shortcuts[1]. The Residential sector electricity consumption (59.6% of national electricity consumption) exceeds the sum of the Industrial and Commercial sectors (11.3 and 29.1% respectively)

[1] The national power infrastructure (made up of 7 Thermal and 3 Hydro generation stations) has estimated total installed, transmission and distribution capacities of 12.5, 5.3, and 7.2 GW respectively. Actual generated, transmitted and distributed electricity were estimated to be 3.9, 3.6 and 3.1 GW respectively. With only 40% national grid connectivity in Nigeria, average daily power supply is estimated to be four hours, and power supply is at best erratic (Momodu *et al.*, 2011; Ogundari and Otuyemi, 2020).

combined (Ogundari *et al.*, 2017). Power supply limitations have been attributed to institutional management failures; electric power equipment theft/fraud; poor financing; energy infrastructure attacks, and antiquated equipment and technologies amongst others (Ogunbiyi, N.D.; Adegbulugbe and Adenikinju, 2011; FMST, 2012; Ajayi, 2013; Ventures Africa, 2014; Ogundari *et al*., 2017; USAID, 2020). These limitations are exacerbated by an exploding population, weakening public infrastructure and institutions, conflict over public and private power generation rights, limited skilled manpower for power infrastructure planning and development, and the vagaries of international energy policy and economics (Atkins Limited, 2014; SPARC, 2014; Olurode *et al*,. 2018; Ugwuanyi, 2018, Stifting and Fabulous Urban, 2018; Arowolo *et al.*, 2019; Ogundari and Otuyemi, 2019 and USAID, 2020). Inadequate grid power supply is the leading cause for private (off-grid) power generation, mainly from environmentally-harmful petrol/diesel generators (Sambo, 2008; Ogundari *et al.*, 2017; FGN, 2018).

The Lagos State scenario is a reflection of the national malaise; 40% of Lagos residents do not have access to the national grid and 80% of residents rely on diesel generators (Atkins Limited, 2014; Onochie *et al.*, 2015; Ogundari and Otuyemi, 2019). Grid supply in Lagos State is about 1000 MW with extant power supply deficits of 9,000 – 10,000 MW (Olurode *et al.,* 2018; Arowolo *et al.*, 2019; Africa Energy (2019). This raises strategic concerns as Lagos State is the economic powerhouse of the country, producing almost 65% of the national economy and having a population of 21 million. Lagos State is estimated to require 16,000 – 27,000 MW of new generation capacity by 2030, with $14 – 33 billion energy generation investment required (MEPB, 2013; Ogunbiyi, N.D.; Atkins Limited, 2014; SPARC, 2014; World Bank, 2015; USAID, 2020). Personalized alternative power generation systems in Lagos State include the mini-grid photovoltaic (PV) systems, the grid-connected gas-powered systems, and the off-grid petrol/diesel generator systems with their adverse environmental, health and climate change implications (African Renewal, 2017; World Bank Group, N. D.; Ogundari and Otuyemi, 2020). These systems are generally inadequate to meet demand.

The Electric Sector Reform Act (2005) loosened the Federal Government's monopoly on the power sector, creating opportunities for the decentralised public sector, non-state actors, and the organised private sector to engage meaningfully in critical electricity infrastructural initiatives (including the off-grid gas power systems) for regional/national development (Ugwuanyi, 2018; Africa Energy, 2019; Ogundari and Otuyemi, 2019). The private-sector participation has been encouraged not only for the needed private capital and technological proficiency for quality service delivery, but also to free public funds for direly-needed socio-economic programmes (African Renewal, 2017; World Bank Group, N. D.; Ogundari and Otuyemi, 2020).

Lagos State, taking cognizance of these reforms, and pursuant to achieving the Lagos State Development Plan (LSDP) (2021-2025) which is dependent on sustainable economic and industrial growth premised on critical infrastructure and strategic power systems delivery (e.g. integrated power projects and off-grid alternative energy systems), enacted the State Electric Power Sector Reform Law (2018), and established the Lagos State Infrastructural Development Initiative and the State Embedded Power Programme (EPP) for 24-hour power supply and domestic electric power development (MEPB, 2013; Ogunsanya *et al.,* 2016; Caleb *et al.*, 2018; Ogundari and Otuyemi, 2019). Critical expected outcomes include 3,000 MW domestic electricity generation by 2023, enhancing State gas-to-power development, enhancing gas supply to Lagos from 500 to 1.25 billion million standard cubic feet (scf) per day by 2023, opening the Lagos gas market to local and international players, and ensuring reduction of the State's reliance on gas from the Niger Delta region for economic development (Caleb *et al.*, 2018; USAID, 2020).

Natural gas-to-electricity generation is considered an appropriate intervention strategy due to the presence of gas infrastructure in the State in particular and Nigeria in general[2] and other factors, namely, its cleaner environmental performance relative to other fossil fuels; its higher energy conversion efficiency; the reliability of supply source at stable and low prices; its inexpensive compact and easy-to-build nature, with quick start-up and shut-down features; and its significant potential to create jobs (Economides and Wood, 2009; Oyedepo *et al.,* 2014, CBN, 2015; GIZ, 2015; Orogun, 2015; Occhiali and Falchetta, 2018; Tahir and Sheriff, 2018). The Lagos State-owned 270-301.5 MW AES gas power station, an enabled IPP, consisting of nine (9) barge-mounted 31.5 MW-gas turbines with public grid connections, was established at the Egbin Thermal Station, Ijede-Ikorodu, Lagos to meet the demands of the Metropolitan Lagos market (Oyedepo *et al.,* 2014). The inadequacies of the plant created the imperative to build new gas power plants, preferably distributed generation or independent electric distribution networks, in the strategic economic area.

Although the grid-connected gas-power system has been deployed for electric power generation augmentation in Lagos State, their concerted efforts to improve power supply in Lagos State have met with limited success with grid electric power supply still inadequate and erratic. Continuous inadequate power supply to Lagos State will stymie the achievement of the State's Development Plan. Lack of technological capabilities in energy infrastructure development would further render ineffective national and regional electric power reform activities, stifle new-player participation in regional critical electric power infrastructural initiatives, and hinder the 24-hour power supply goal of the State. This will also limit public funds for direly-needed socio-economic development programmes.

For the Metropolitan Lagos residential sector, the adoption of off-grid alternative power options in general and natural gas-powered systems in particular to address the inadequate grid power supply is hindered by ineffectual techno-economic assessments of the strategic options. These techno-economic assessments are an essential, effective planning/evaluation tool for the selection of critical energy infrastructure projects. The goal of this study therefore is to provide a viable critical assessment of the natural gas-powered (off-grid) alternative power option in Lagos State by assessing appropriate site locations for the natural gas plants in the State; determining the technical specifications and economic viability of the natural gas-powered system; and examining the techno-economic and environmental benefits of the system as a strategic template for interested stakeholders across the State and in Nigeria.

1.1. Lagos State, Nigeria

Lagos State, located on the coast in Southwestern Nigeria, has its capital at Ikeja. The State is the smallest State in Nigeria by landmass (3,577 sq. km) yet has the highest population (an estimated 21 million people). Lagos State consists of 5 Administrative Divisions (Ikeja, Lagos, Badagry, Ikorodu and Epe), divided into 20 Local Government Areas (LGAs) and 57 Local Council Development Areas (LCDAs) (MEPB, 2013).

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[2] Nigeria, with the world's 9th largest proven natural gas reserves of 193.35 – 198.72 trillion cubic feet (tcf), estimated unproven reserves of about 600 tcf, and annual production of 2.920 tcf, is in a vantage position for natural-gas electric power production (BP, 2018; Biose, 2019)

Lagos State is Nigeria's main economic, commercial and financial hub, and the State's Gross Domestic Product (GDP) ($136.6 billion) accounted for almost 30% of national total GDP, 90% of Nigeria's foreign trade and 70% of all industrial investments (MEPB, 2013; Ehingbeti, 2021). Lagos State, with its diverse economy, is the West African economic hub, largest ICT market in sub-saharan Africa, a major financial centre in Africa, and would be Africa's fifth largest economy if it were an independent country (Oteri and Ayeni, 2016; ft.com, 2018; Lagos State Government, 2018).

The City of Lagos, Nigeria's capital city from 1914 to 1991, is the World's sixth megacity, an expanding global urban agglomeration, and is Nigeria's largest city, principal port, main economic hub and major educational and cultural centre (PwC, 2015). The Lagos megacity region (also known as the Lagos Metropolitan Area, Metropolitan Lagos, Greater Lagos or Lagos Greater Metropolitan Area), is an urban agglomeration or conurbation, which accounts for about 37% of the State total land area, 85% of the State population, and 10% of national GDP (PwC, 2015). The Lagos Metropolitan Area covers 16 of the State's 20 LGAs and 57 LCDAs, and is located on four principal islands (Lagos Island, Ikoyi, Iddo and Victoria Island) and the mainland suburbs (including Yaba, Apapa, Oshodi, Shomolu and Ikeja) (MEPB, 2013). The Megacity region has extended into five LGAs of adjourning Ogun State (Sagamu, Ifo. Ado Odo/Ota, Obafemi Owode and Ewekoro), necessitating strategic approaches to critical infrastructure development (Campbell, 2012; Ogunsanya *et al*., 2016; Stiftung and Fabulous Urban, 2018).

Figure 1: Map of Nigeria showing Lagos State in Red
Source: Lagos State Government (2009)

Figure 2: The 16 LGAs of Metropolitan Lagos
Source: Lagos State Government (2009)

1.2. The Distributed Generation (DG) Natural Gas-to-Power Technology

The Distributed Generation (DG) system deploys individual (decentralized), small-scale electric generation technologies close to the end users they serve. DG technologies may be modular or renewable-energy based, have capacities up to 10 MW, and range from small, low-output, back-up generators for centralized electric utilities support to larger, independent generators. DG technologies provide lower-cost, higher-reliability, higher-efficiency, higher-security with fewer environmental consequences electricity relative to the traditional, centralized power utility. They also enable increased local control over electricity supply and reduce transmission electricity losses. Various forms of on-site, natural gas-fired distributed generation include fuel cells, gas-fired reciprocating engines, industrial natural gas-fired turbines, micro-turbines, and Combined Heat and Power (CHP) systems (Virginia Technology, 2007; NaturalGas.org, 2013).

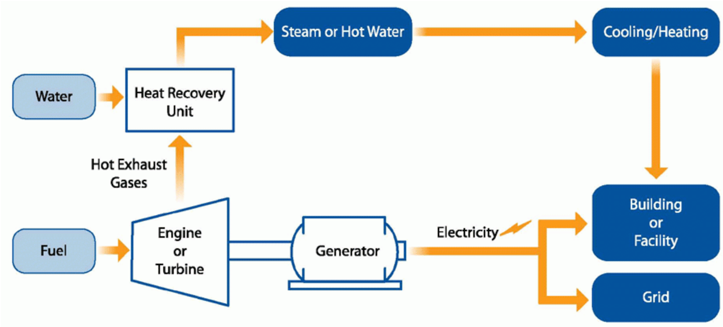

Figure 3: Combined Heat and Power System – Combustion Turbine, or Reciprocating Engine, with Heat Recovery Unit (A DG Natural Gas-to-Power Process)
Source: EPA (N. D.)

2. Methodology

This energy policy/strategic analysis study utilized an energy project foresight analysis framework. This framework inculcates Technology Foresight Analysis (TFA) methodology in Energy Systems development (Ogundari and Otuyemi, 2020). Technology Foresight is a "systematic, participatory process, involving gathering intelligence and building visions for the strategic, medium-to-long-term future and aimed at informing present-day decisions and mobilizing joint actions" (Yim, 2010). Thus it is not the ability to predict the future, but the process to creating the future desired (Yim, 2010; Ogundari and Otuyemi, 2020). TFA utilises, independently or in an amalgamation, Qualitative (Backcasting, literature reviews, expert panels, genius forecasting, strategic assessment, etc), Semi-quantitative (roadmapping, game-simulation, Delphi Technique, System/Structural analysis etc), and Quantitative (benchmarking, extrapolation, modeling simulation, bibliometrical analysis etc) techniques where appropriate (Yim, 2010).

To achieve objective (i), Plant Location Analysis was carried out to determine three out of the five Divisions in Lagos State (Lagos, Ikeja, Badagry, Ikorodu and Epe) as sites for the natural gas-powered (off-grid) plants. Parameters of the plant location analysis include accessibility to raw materials (natural gas), nearness to the market, availability of labour, transport facilities/services, availability of fuel and power, availability of water amongst others. A plant location analysis questionnaire set was administered on 4 purposively selected energy planning officers and 3 purposively selected urban and regional planning officers in the Lagos State Ministry of Energy and Mineral Resources. The respondents measured each plant location parameter in each of the 5 divisions on a Likert-like scale (where 1 was the minimum score and 10 the maximum score). The modal value of the data set of each parameter for each division was selected as the most accepted rating. The total scores for each division were determined and ranked. The divisions with the three highest scores were selected.

To achieve objective (ii), a natural-gas (off-grid) electric power system design analysis was executed. A Distributed Generation (DG) Combined Heat and Power (CHP) system with an 8 MW-provision target was purposively selected for analysis. This is because this system type is a modular electricity-generation technology with capacities up to 10 MW and other technical specifications which fit in the off-grid, 10 MW-maximum power generation limits in the Electric Power Sector Reform Act (2005). The technical and costs specifications for the CHP system were obtained from literature. These included slack or unused system productive potential, uninterrupted electricity supply estimated duration per day, electricity to natural gas ratio, natural gas costs, Lagos State electricity residential rates, natural-gas power plant land area requirements, costs of land in Lagos, and combine cycle unit costs. Techno-economic parameters included initial investment costs – cost of the combined cycle unit, land costs, building costs, transformer and electric features costs and working capital; annual operation costs – natural gas procurement costs, personnel costs, utilities, depreciation, insurance and taxes, maintenance and repairs, administrative costs, research, development and analysis costs; and annual estimated revenues from projected electricity sales. An energy project financial management template detailing the percentage of each operations cost item relative to the total operations cost was developed based on literature (EIA, 2016, Strata, 2017; EIA, 2020; PennState, N.D.), the expert opinion of the energy planning specialists interviewed, manufacturers/equipment vendors' price lists and financial analysis reports (PwC, 2019). Profitability indices (Net Present Value (NPV), Break-even and Payback Period) were determined using their appropriate methods. The techno-economic viability analysis also included determining comparative fuel costs for the natural-gas powered and diesel-powered (off-grid) alternative power supply systems.

To achieve objective (iii), Diesel-to-kWh and diesel-to-CO_2 emission conversion factors were obtained from literature. The data were used to determine total diesel consumption and CO_2 emissions if diesel generator-based off-grid alternative power supply had been employed. The comparison between diesel-to-CO_2 emissions by the natural-gas powered and diesel-powered (off-grid) alternative power supply systems were used to determine the Environmental benefits of the natural-gas powered (off-grid) alternative power supply system.

3. Results

The calculations of the study are presented in this section.

3.1. Determination of the Locations for the Municipal Natural-Gas Powered (Off-Grid) Alternative Power Systems in Lagos State

The analysis of plant location parameters (Table 1) indicate that Lagos, Ikeja and Badagry Divisions of Lagos State are the 3 most suitable Divisions for the siting of the natural gas plants in Lagos State. The Lagos Division with ratings of 8.55 out of a possible 10 was ranked 1st, the Ikeja Division (ratings: 8.18) was ranked 2nd while the Badagry Division (ratings: 7.91) was ranked 3rd. The towns Apapa (Lagos Division), Ikeja (Ikeja Division) and Festac Town (Badagry Division) were purposively selected for the large number of residential estates situated in and around them.

3.2. Technical and Cost Specifications for the Natural Gas-Powered Stations in the Selected Areas in Lagos State

The purposively selected natural-gas power station for analysis is a Distributed Generation CHP system to provide 8 MW of electricity. This power station is estimated to have 60% energy efficiency (Momodu *et al.*, 2011).

i. Minimum estimated size for the power station

Taking into cognisance the energy efficiency of the power station and the ever-growing population in Lagos State, a slack or unused system productive potential of 1MW was provided for in the power system design (Momodu *et al.*, 2011).

Thus, assumed power generation = 8 + 1 MW = 9MW

$$Minimum\ Estimated\ installed\ power\ generation = \frac{Power\ (W)}{Energy\ Efficiency\ (\%)} \quad (1)$$

$$Minimum\ Estimated\ installed\ power\ generation = \frac{9\ MW}{0.6} = 15\ MW$$

The appropriate planning design for the natural gas power plant would be 15 MW.

Table 1: Plant Location Analysis of Municipal Natural-Gas Powered (Off Grid) Alternative Power Systems Development in Lagos State

	Ikeja (Ikeja)	Lagos (Apapa)	Badagry (Festac Town)	Ikorodu (Ikorodu)	Epe (Epe)
Accessibility to raw materials (natural gas)	7	8	7	8	7
Nearness to the market	10	10	10	6	5
Availability of labour	10	10	10	7	6
Transport facilities/services	8	9	7	9	6
Availability of fuel and power	9	9	9	8	6
Availability of water	7	9	6	8	7
Nature of climatic conditions	7	7	7	7	7
Government policies and influences	8	8	7	7	6
Availability of finance	9	9	9	8	7
Availability of Infrastructural facilities	8	8	8	6	5
Disposal of waste	7	7	7	7	6
Weighted Average	8.18	8.55	7.91	7.36	6.18
Location Decision Ranking	2nd	1st	3rd	4th	5th

**(On a Scale of 1 – 10 where 1 is lowest Rate and 10 highest Rate)*

ii. Total electricity generation

The estimated duration for uninterrupted electricity supply per day is 16 hours (Ogundari and Otuyemi, 2020).

$$Electricity\ generation\ per\ day = Power\ (W) \times Time\ (h) = Wh/day \quad (2)$$

$$Total\ daily\ electricity\ generation = (8MW\ \times 16\ hours)/day = 128\ Wh/day$$

$$Total\ Annual\ electricity\ generation = 128 \frac{Wh}{day} x\ 365\ days = 46{,}720\ MWh/year$$

This electricity generation (128MWh/day; 46,720MWh/year) is assumed to be guaranteed power supply to each of the determined divisions of Metropolitan Lagos.

iii. Natural gas requirement:

1 kWh of electricity requires 3.41 standard cubic feet (scf) of Natural Gas (EPA, N. D.)

Thus, Daily electricity generation of 128 MWh would require:

$$128\ MWh\ of\ electricity\ \equiv (128000 \times 3.41)$$
$$\equiv 436{,}480\ scf\ of\ Natural\ Gas$$

Annual electricity generation of 46,720 MWh would require:

$$46{,}720\ MWh\ of\ elelctricity\ \equiv (436{,}480 \times 365)$$
$$\equiv\ 159{,}315{,}200\ scf\ of\ Natural\ Gas$$

This is approximately 160,000,000 scf of Natural Gas.

iv. Cost of Natural Gas

Natural gas costs US$ 1.76 per 1000 scf (WEC, 2020) (US$ 1.76 = ₦721.60 @ ₦410 per US$ as at September 2021 rates)

$$Annual\ Natural\ gas\ costs = \frac{160{,}000{,}000}{1000} \times 721.60$$
$$= ₦\ 203{,}202{,}560$$

v. Cost of electricity consumption

Electricity residential rates in Lagos State are ₦42.44 per kWh[3]

$$Electricity\ consumption\ costs\ per\ day$$
$$= 128{,}000 \times ₦42.44 =\ ₦5{,}432{,}320.00$$
$$Annual\ electricity\ consumption\ costs$$
$$= 46{,}720{,}000 \times ₦42.44 =\ ₦1{,}982{,}796{,}800$$

vi. Total land area required for the Natural Gas plants

An average natural-gas power plant requires approximately 0.343 acres per MWe produced (Strata, 2017).

For the proposed 15MW Natural-Gas power plant,

$$Total\ land\ requirements = 0.343\ \times 15 = 5.145\ acres$$

Since 1 acre is approximately 6 plots of land,

$$Total\ land\ requirements\ (5.145\ acres)$$
$$= 5.145\ \times 6 = 30.87\ or \sim 31\ plots\ of\ land$$

vii. Cost of land in the selected areas of Lagos State (Nigeria Property Centre, 2021):

Lagos Division (Apapa)

5820 sq metres (1.438 acres) of industrial land cost ₦578.1 million

5.145 acres will cost

$$₦\left(\frac{578{,}100{,}000}{1.438}\ X\ 5.145\right) = \sim ₦\ 2.07\ \text{billion}$$

Ikeja Division (Ikeja)

22000 sq metres (5.436 acres) of Industrial land cost ₦1,258.7 million

5.145 acres will cost

$$₦\left(\frac{1{,}258{,}700{,}000}{5.436}\ X\ 5.145\right) = \sim\ ₦1{,}197.2\ \text{million}$$

Badagry Division (Festac Town)

15 acres of mixed-purpose land cost to ₦1,578.5 million

5.145 acres will cost

$$₦\ \left(\frac{1{,}578{,}500{,}000}{15}\ X\ 5.145\right) = ₦541.2\ \text{million}$$

viii. Cost of Distributed Generation CHP system (Combined cycle unit)

Average cost for combine cycle unit

$$= \sim \text{US\$ 614/kW (Strata, 2017) or ₦ 251,740/kW}$$
$$Estimated\ costs\ for\ a\ 15\ MW\ combined\ cycle\ unit$$
$$= ₦\ 251{,}740\ \times 15{,}000$$
$$= ₦\ 3{,}776.1\ \text{million}$$

3.3. Techno-economic analysis of the natural gas-powered (off-grid) alternative power systems in the selected divisions of Lagos State

It is imperative to determine the viability and payback period of the natural gas power supply system project as an input to project investment decision making by critical stakeholders. Table 2 reveals the cost and revenue estimates for the natural gas-powered (off-grid) alternative power systems in the determined areas of Lagos Division (Apapa), Ikeja Division (Ikeja) and Badagry Division (Festac Town). The estimated difference in capital costs is in the various costs of land. Annual operating costs (US$ 2, 156, 300) were estimated for each location. With estimated annual revenues of US$ 2,990,080 per location, the estimated profits were US$ 838,162.94 per location.

The profitability index showed Net Present Value of US$ 5,028,977.66, break-even time of 1 year, and payback period of 14 years per location. Thus the adoption of natural gas-powered (off-grid) alternative power systems in Lagos (Apapa), Ikeja (Ikeja) and Badagry (Festac Town) Divisions of Lagos State were determined to be viable projects which would break even in 1 year. Payback period for the investments were estimated to be 12 – 20 years for Lagos Division (Apapa), 12 – 15 years for the Badagry Division (Festac Town) and 12 – 17 years for the Ikeka Division (Ikeja).

3.3.1. Net Present Value Analysis for the natural gas-powered systems

The Net Present Value (NPV) is determined by the net cash flow over the project lifespan (20 years) discounted to the present less the Initial Investment (Blank and Tarquin, 2012; Shah, 2012).

The study assumed that the value of the annual profits would be the same over the 20-year project lifespan and be equal to the first year profit of ₦ 343,650,000.

The value of the Depreciation was also assumed to be the same over the project lifespan and be equal to the first year Depreciation of ₦ 304,070,000.

Thus,

$$\text{Total value of profits over the 20} - \text{year project lifespan}$$
$$=\ ₦\ 343{,}650{,}000\ X\ 20$$
$$= ₦\ 6{,}872{,}936{,}108$$

$$\text{The project salvage value}$$
$$=\ \text{Initial Investment less total depreciation}$$
$$=\ ₦\ 6{,}732{,}200{,}000 - (304{,}070{,}000\ X\ 20)$$
$$=\ ₦\ 650{,}800{,}000$$

$$NPV\ = -\ \text{Initial Investment}$$
$$+ \text{Total project Annual Profits discounted to the Present}$$
$$+ \text{Salvage}$$

Value discounted to the Present

$$NPV\ = -\ \text{Initial Investment}\ +\ F(P/F, I, N)$$
$$+ \text{Salvage Value}\ (P/F, I, N)$$

where,

Number of years = 1 year.

[3] This is the rate as charged by the Ikeja Electricity Distribution Company (IKEDC) and Eko Electricity Distribution Company (EKEDC) as at the time of the study These DISCOs distribute power across Lagos State.

Interest Rate = 10% (Commercial loan rate obtained from the CBN as at July 2021)

F(P/F, I, N) = ₦ 6,872,936,108 (0.9091)
= ₦ 6,248,186,216

Salvage Value (P/F, I, N) = ₦ 650,800,000 (0.9091)
= ₦ 591,642,280

Table 2: Techno-Economic Assessment of the Natural Gas-Powered (Off-Grid) Alternative Power Systems in Selected Divisions of Lagos State

Costs	Lagos Division (Apapa) (₦ million)	Badagry Division (Festac Town) (₦ million)	Ikeja Division (Ikeja) (₦ million)
Capital Costs			
15 MW Combined Cycle Unit	3,776.10	3,776.10	3,776.10
Land	2,070.50	541.20	1,197.20
Administrative Building	263.22	263.22	263.22
Transformers + electrical features	89.38	89.38	89.38
Working Capital	533.00	533.00	533.00
Total Investment	*6,732.20*	*5,202.90*	*5,858.90*
Operations Costs (Annual)			
Natural Gas (Raw Material)	203.20	203.20	203.20
Personnel	76.25	76.25	76.25
Utilities (Electricity, Water)	67.89	67.89	67.89
Depreciation	304.07	304.07	304.07
Various costs (insurance, taxes)	724.37	724.37	724.37
Maintenance & Repairs	212.85	212.85	212.85
Administrative costs	19.76	19.76	19.76
Research, Development & Analysis	30.77	30.77	30.77
Total Operating Costs (Annual)	*1,639.15*	*1,639.15*	*1,639.15*
Estimated Revenue (Annual)			
Projected Electricity Sales of 46,720 MWh @ ₦ 42.44/kWh	1,982.80	1,982.80	1,982.80
Estimated Profit (Annual)	343.65	343.65	343.65
Profitability Index			
Net Present Value (₦ million)	107.63	1,636.93	980.93
Break-even time (Years)	1	1	1
Payback Period (Years)	12 – 20	12 – 15	12 – 17

NPV for Apapa Station = – Initial Investment + F(P/F, I, N) + Salvage Value (P/F, I, N)
= – ₦ 6,732,200,000 + ₦ 6,248,186,216 + ₦ 591,642,280
= ₦ 107,628,496

NPV for Festac Town Station = – Initial Investment + F(P/F, I, N) + Salvage Value (P/F, I, N)
= ₦ 5,202,900,000 + ₦ 6,248,186,216 + ₦ 591,642,280
= ₦ 1,636,928,496

NPV for Ikeja Station = – Initial Investment + $F\left(\frac{P}{F}, I, N\right)$ + Salvage Value (P/F, I, N)
= ₦5,858,900,000 + ₦ 6,248,186,216 + ₦ 591,642,280
= ₦ 980,928,496

The Break-even time is the period (in Years) in which the gains from an economic activity equal the costs incurred in pursuing it (Blank and Tarquin, 2012; Shah, 2012). Table 2 shows that the break-even time occurs in the first year of operation.

3.3.2. Payback Period Analysis for the natural gas-powered systems

The Payback Period Calculation was used for analysis (Blank and Tarquin, 2012; Shah, 2012).

$$\text{Payback Period} = \frac{\textbf{Initial Investment}}{\textbf{Annualized expected cash inflow}} \quad (3)$$

Thus,

$$\text{Payback Period for Apapa Station} = \frac{6{,}732{,}200{,}000}{343{,}650{,}000}$$
= 19.5 years or Approx. 20 years

$$\text{Payback Period for Festac Town Station} = \frac{5{,}202{,}900{,}000}{838{,}162.94}$$
= 15 years

$$\text{Payback Period for Ikeja Station} = \frac{5{,}858{,}900{,}000}{343{,}650{,}000}$$
= 17 years

It is important to note that land appreciates over time, thus it is reasonable to deduct the cost of land and the working capital from the estimation of payback period. If this is taken into consideration, the Payback Periods for each Station would be the same as all other capital costs are uniform.

Thus,

$$\text{Payback Period} = \frac{4{,}128{,}700{,}000}{343{,}650{,}000} = 12 \text{ years}$$

Consequently, payback period for the Apapa, Festac Town and Ikeja Stations were estimated to be in the ranges 12 – 20 years, 12 – 15 years, and 12 – 17 years respectively.

3.4. Environmental and Cost benefits of Natural gas power supply system's deployment in each Metropolitan Lagos area

The environmental and cost benefits of natural gas alternative power supply to Metropolitan Lagos were analyzed in this section. In Lagos, individuals, households and corporations rely on diesel-powered generators for alternative power generation. The diesel fuel consumed emits carbon dioxide (CO_2) which is environmentally harmful (Ogundari *et al.*, 2017), and the adoption of natural gas power supply would lead to the reduction of the environmentally harmful CO_2 emissions. (Note: carbon dioxide emissions by burning natural gas relative to diesel are in the ratio 1:1.38 (American Geosciences Institute, 2020)).

3.4.1. Electric power supply from a diesel generator alternative power option

One litre of diesel can produce 10 kWh of energy (Oviroh and Jen, 2018)

In each Division:

Daily guaranteed electricity generation = 128 MWh or 128,000 kWh

Thus,

$$128{,}000 \text{ kWh would require } = \frac{128{,}000 \; x \; 1}{10}$$
$$= 12{,}800 \text{ litres of diesel per day}$$

A litre of diesel used for power generation emits 2.68 kg of carbon dioxide (CO_2)

Thus,

$$12{,}800 \text{ litres of diesel consumption } \equiv (2.68 \text{ X } 12{,}800)$$
$$= 34{,}304 \text{ kg of } CO_2$$

3.4.2. Annual and lifecycle estimates for natural gas and diesel-based electricity generation

Table 3 shows that the natural gas-based electric power generation would give annual CO_2 emission reductions of 3.45 Metric Kilotonnes per division relative to the diesel-based power generation, and 11.27 Metric Kilotonnes across the 3 Divisions.

Table 3: Annual Estimates for Natural Gas and Diesel-based Electricity Generation

	In Each Division		Across 3 Divisions	
	Natural gas generators	Diesel generators	Natural gas generators	Diesel generators
Electricity generation (MWh)	46,720	46,720	150,160	150,160
Fuel requirement	160,000,000 scf	4,672,000 Litres	480,000,000 scf	14,016,000 Litres
CO_2 emissions (Metric Kilotonnes)	9.07	12.52	27.21	37.56
CO_2 emissions savings (Metric Kilotonnes)	3.45		10.35	

Table 4 shows that over its 20-year lifecycle, the natural gas-based electric power generation would give annual CO_2 emission reductions of 68.96 Metric Kilotonnes per division relative to the diesel-based power generation, and 206.88 Metric Kilotonnes across the 3 Divisions.

Table 4: Estimates over the Lifecycle of the Natural Gas-powered Off-Grid Systems

	In Each Division		Across 3 Divisions	
	Natural gas generator	Diesel generator	Natural gas generator	Diesel generator
Electricity generation (MWh)	934,400	934,400	2,803,200	2,803,200
Fuel requirement	3,200,000,000 scf	93,440,000 Litres	9,600,000,000 scf	280,320,000 Litres
CO_2 emissions (Metric Kilotonnes)	181.46	250.42	544.38	751.26
CO_2 emissions savings (Metric Kilotonnes)	68.96		206.88	

3.4.3. Comparative Fuel Costs for the Electric Power Systems

Annual Fuel Costs:

In Each Division, with Annual Electricity Generation of 46,720 MWh

i. Estimated diesel required = 4,672,000 Litres
ii. Natural gas required = 160,000,000 Scf (approximation)
iii. Cost of diesel @ ₦188.60/litre = 4,672,000 x 188.60
 = ₦ 881,139,200
iv. Cost of natural gas @ ₦0.72/scf = 160,000,000 x 0.72
 = ₦ 115,456,000
v. Cost differences in fuel supply
 = ₦ (881,139,200 − 115,456,000) = ₦ 765,683,200

Life Cycle Fuel Costs:

(The natural-gas powered off-grid system is estimated to have a 20 year lifespan)

Thus, in Each Division (Using annual data for consideration):

i. Total electricity generation = 46,720 MWh X 20
 = 934,400 MWh
ii. Estimated diesel required = 4,672,000 Litres X 20
 = 93,440,000 Litres
iii. Natural gas required = 160,000,000 scf X 20
 = 3,200,000,000 scf
iv. Cost of diesel = ₦ 881,139,200 X 20
 = ₦ 17,622,784,000
v. Cost of natural gas = ₦ 115,456,000 X 20
 = ₦ 2,309,120,000
vi. Cost differences in fuel supply = ₦ 765,683,200 X 20
 = ₦ 15,313,664,000

In each Division, with annual electricity generation of 46,720 MWh, fuel supply cost differential estimates were ₦ 765.7 million; across the 3 Divisions, with annual electricity generation of 140,160 MWh, fuel supply cost differential estimates were ₦ 2.30 billion. Across the 20-year life cycle of the gas-powered electric power plant, in each Division, with estimated electricity generation of 934,400 MWh, fuel supply cost differential estimates were ₦ 15.3 billion; across the 3 Divisions, with estimated electricity generation of 2,803,200 MWh, fuel supply cost differential estimates were ₦ 45.9 billion.

4. SUMMARY AND CONCLUSION

This study focused on techno-economic assessment of natural gas-powered (off-grid) alternative electric power supply option for municipal residential complexes in Lagos State, Nigeria as a mitigation strategy to erratic power supply under the State's embedded power programme and a strategic template for other stakeholders in Nigeria in general and Lagos State in particular. An energy project foresight analysis framework comprising planning and strategic foresight methods was used.

The plant location analysis established that Lagos (Apapa), Ikeja (Ikeja) and Badagry (Festac Town) Divisions of Lagos State were the most appropriate locations for the gas power plant initiatives in the State. The energy project technical specifications analysis established an individual natural-gas CHP power plant design for 15 MW built on 5.145 acres of land, consuming approximately 160 million scf of natural gas annually, and generating 46,720 MWh of electricity annually. This power plant would cost an estimated ₦ 3.78 billion, consume ₦ 203.2 million worth of natural gas annually, and generate estimated revenues of ₦ 1.98 billion annually. With estimated total investments of ₦ 5.2 – 6.73 billion, and estimated annual profits of ₦ 343.65 million per location, Profitability Indices indicated positive Net Present Values across the Divisions, break-even time within the first year of operation, and payback periods over 12 – 20 years. Fuel cost differential estimates across the 3 Divisions were ₦ 2.30 billion annually and ₦ 45.9 billion over the 20-year lifecycle of the natural gas power plant system., while CO_2 emissions saving estimates across the 3 Divisions were 10.35 Metric Kilotonnes annually and 206.88 Metric Kilotonnes over the lifecycle of the natural gas power plant system.

The study concluded that the municipal natural gas-powered (off-grid) alternative electric power initiative for Lagos State electric power supply is technically feasible, environmentally reasonable and economically viable, and suitable to be deployed as a strategic template for other stakeholders in Nigeria in general and Lagos State in particular.

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