Pan African University
Institute of Water
and Energy Sciences

# PAN-AFRICAN UNIVERSITY
## INSTITUTE FOR WATER AND ENERGY SCIENCES
## (including CLIMATE CHANGE)

# Master Dissertation

Submitted in partial fulfillment of the requirements for the award of Master of Science degree in

[Energy Policy]

Presented by

***Chibuzo Maduka NWABUE***

**Economic and environmental comparison of a natural gas plant and Solar PV systems for rural electrification in Nigeria: a case study of Iyiora Anam**

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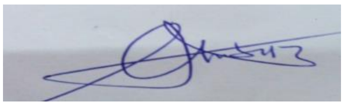
## DECLARATION

I Chibuzo Maduka Nwabue, hereby declare that this thesis titled "Economic and environmental comparison of a natural gas plant and Solar PV systems for rural electrification in Nigeria: a case study of Iyiora Anam" is my original work and that no part of it has been presented for any academic purpose or other purposes that is against the Pan African ethics and conduct of research in any other time before any University. I also declare that all other works of people cited in this thesis have been duly recognized as required of academic rules and ethics.



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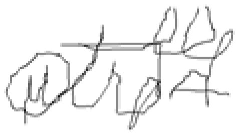

19, August 2018

**Professor Hassan Qudrat-Ullah (PhD)**

# DEDICATION

I dedicate this write up to God Almighty, my parents Prince F.N. and Mrs Edith Nwabue, family members and friends who have supported me in attaining this height in education.

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This project would not have been possible if not for the grace and mercy shown to me by God Almighty. To my family, especially my parents and siblings, I am very grateful for all being there for me all these years, this journey would not have reached this far if not for your support, prayers and encouragement.

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May God bless and reward you all.

**ABSTRACT**

Electricity access rate in Nigeria have been all time low with 70% of rural dwellers lacking access to electricity, despite policies aimed at providing electricity to these offgrid communities. Therefore, in a bid to provide electricity access to Iyiora Anam, a rural off-grid community in Nigeria and ensuring that carbon emissions into the environment are accounted for, this study provides an economic and environmental comparison of a Natural gas plant and Solar PV systems utilizing a mini-grid system. The study adopted the Theoretical framework of the Levilized Cost of Energy employing data gotten from analysis of the literature, survey approach and Offgrid RE developers and Equipment suppliers which was analysed using HomerPro software for simulating different systems for microgrid and other distributed electrical power systems. The results of the analysis show that Solar PV has a lower levelized cost but a higher Capital cost 90% higher than the Natural gas plant which has a lower capital cost but a higher levelized cost of electricity. When emission cost were modelled into the Natural gas powered system, its levelized cost increased further to show the uncompensated impact generating electricity with Natural gas. Also, the result of the sensitivity analysis to assess the likely effect variations in some parameters like fuel cost, emission charges and annual average solar irradiance will have on the cost of electricity generation on the site shows that fuel price and cost of electricity generation have a positive relationship, also emission charges and the cost of generating electricity exhibited a positive relationship. However, the annual average solar irradiance were discovered to have varying relationship with cost of electricity generation, as higher or lower average solar irradiance reduces the performance of the Solar PV system thus leading to a higher cost of electricity generation. The study recommends the need to develop policies which will further ensure that power system components (Panels, Batteries and Inverters) are subsidized so as to enable private investors have confidence in investing their funds in the offgrid areas especially for solar which have a high capital cost.

# RÉSUMÉ

Le taux d’accès à l’électricité au Nigéria ont toujours été faible; 70% des populations rurales sont privés d’accès à l’électricité malgré les politiques visant à fournir de l’électricité à ces communautés. Par conséquent, en vue de fournir un accès à l'électricité à Iyiora Anam, une communauté rurale hors réseau au Nigeria et de s'assurer que les émissions de carbone dans l'environnement sont comptabilisés, cette étude fournit une comparaison économique et environnementale d'une usine de gaz naturel et de systèmes photovoltaïques en utilisant un système de miniréseaux.

L'étude a adopté la théorie du coût moyen actualisé de l'énergie, utilisant des données issues de l'analyse de la littérature, de la méthode d'enquête personnalisées et des promoteurs d’énergie renouvelable et fournisseurs d'équipements, analysé à l'aide du logiciel HomerPro pour simuler différents systèmes de microréseau et les autres systèmes électriques distribués. Les résultats de l’analyse montrent que le coût actualisé de systèmes photovoltaïques est inférieur, ayant un coût de 90% supérieur en capital à l’usine de gaz naturel, dont le coût en capital est moins élevé mais le coût de l’électricité est plus élevé. Lorsque le coût des émissions a été modélisé dans les centrales thermiques au gaz naturel, son coût moyen actualisé a encore augmenté pour montrer l'impact sans répercussion générant de l'électricité avec du gaz naturel. En outre, l’analyse de sensibilité visant à évaluer les effets probables de certains paramètres tels que le coût du carburant, les redevances d’émission et l’irradiation solaire annuelle moyenne, auront une incidence sur le coût de la production d’électricité dans un endroit donné, montrant que le prix de carburant et le coût de la production d’électricité a une relation positive. Egalement, les redevances sur l'émission et le coût de production de l’électricité ont montré une relation positive. Cependant, on a découvert que le rayonnement solaire moyenne annuelle avait des relations variables avec le coût de la production d’électricité, car une irradiation solaire moyenne plus élevée ou plus faible réduit la performance du système solaire photovoltaïque, entraînant ainsi un coût de production plus élevé. L'étude recommande la nécessité de développer des politiques qui garantiront que les composants du système électrique (panneaux, batteries et onduleurs) sont subventionnés afin de permettre aux investisseurs privés de faire confiance en investissant leurs fonds dans les zones hors-réseau, en particulier pour l'énergie solaire qui a lr haut cout d’investissement.

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| | |
|---|---|
| AC | Alternating Current |
| BBL | Billion Barrels per Day |
| CAPEX | Capital Expenditure |
| CCGT | Closed Cycle Gas Turbine |
| $CO_2$ | Carbondioxide |
| COP | Conference of Parties |
| CSP | Concentrated Solar Power |
| DC | Direct Current |
| DisCos | Distribution Companies |
| ECN | Energy Commission of Nigeria |
| EPA | Environmental Protection Agency |
| EPSRA | Electricity Power Sector Reform Act |
| FGN | Federal Government of Nigeria |
| FMPS | Federal Ministry of Power and Steel |
| GEC | Global Energy Company |
| GenCos | Generation Companies |
| IEA | International Energy Administration |
| IPPs | Independent Power Producers |
| IRENA | International Renewable Energy Agency |
| KM | Kilometre |
| KV | Kilo Volts |
| KVA | Kilo Volts Amperes |
| KW | Kilo Watts |

| | |
|---|---|
| kWh | Kilo Watts hour |
| LCA | Life Cycle Analysis |
| LCOE | Levelized Cost of Electricity |
| LGA | Local Government Area |
| LGAH | Local Government Area Headquarters |
| LULUCF | Land Use, Land-use Charge and Forestry |
| $M^3$ | Cubic Meters |
| MW | Mega Watts |
| NBET | Nigerian Bulk Electricity Trader |
| NEMSA | Nigeria Electricity Management Service Agency (NEMSA) |
| NEPA | Nigerian Electricity Power Authority |
| NERC | Nigerian Electricity Regulatory Commission |
| NPC | Net Present Cost |
| NPV | Net Present Value |
| NREEEP | National Renewable Energy and Energy Efficiency Policy |
| O & M | Operation and Maintenance |
| OCGT | Open Cycle Gas Turbine |
| OPEX | Operational Expenditure |
| OPL | Oil Production Licence |
| PMS | Premium Motor Spirit |
| PPA | Power Purchase Agreement |
| PV | Photovoltaic |
| PVGIS | Photovoltaic Geographical Information System |
| RE | Renewable Energy |

| | |
|---|---|
| REA | Rural Electrification Agency |
| SCOE | Social Cost of Electricity |
| SDGs | Sustainable Development Goals |
| TCF | Trillion Cubic Feet |
| $tco_2e$ | tons of Carbondioxide emissions |
| TLCC | Total Life Cycle Cost |
| TV | Television |
| US$ | United States Dollars |
| WACC | Weighted Average Cost of Capital |

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background to the Study

Lack of access to modern energy services have been one of the major problem of the developing countries. Africa and Asia countries have been the worse hit by this menace of lack of access to modern energy services. In Africa, especially among the countries living in the south of Sahara, access to electricity is below 40%. The region has an estimated population of 915 million people, out of which more than 625 million people lack access to electricity, while many who have access, are faced with unreliable supply of electricity not meeting their daily needs (IEA, 2014). The rural areas are the most hit by this problem especially those residing in the south of Sahara, with an average access rate of 10% (Huet and Boiteau, 2017). These population mostly in spartial settlements rely on traditional burning of solid biomass for their energy needs (mostly for cooking and heating). This practice is very harmful to the environment as it leads to the emission of carbon dioxide into the atmosphere. It also leads to respiratory health challenges as it has been identified as leading to about 79000 deaths annually (World Health Organization, 2007). It has also led to a lot of social imbalance mainly on the part of the female folks residing in the rural areas who use their productive time wandering around the bush in search of woods for cooking along with their daughters. This has also impacted negatively on the girl child, whose right to education are denied through such practices of following their mothers to the bush in search of Fuelwood.

In Nigeria, access to electricity is very low, despite the abundant renewable and non-renewable energy resources in the country. According to British Petroleum (2017), Nigeria has a proven reserve of 186.6 Trillion Cubic Feet (TCF) of natural gas, making it the country with the highest deposit of Natural gas in Africa and tenth in the world. It also have a proven crude oil reserve of 37.1 Billion barrels, the second highest reserve in Africa, after Libya. The country holds a significant deposit of coal and renewable energy resources like Solar, Wind, Biomass and Hydro which is capable of delivering enough electricity for Nigeria when harnessed.

**Table 1.1: Energy Potentials in Nigeria**

| **Resource** | **Potential** | **Remark** |
|---|---|---|
| Crude oil | 37.1 bbl | Not presently used for producing grid connected electricity. |
| Natural gas | 186.6 TCF | Use for powering 81% of grid connected power plants |
| Coal | 639 million Tonnes proven | Not presently used for producing grid connected electricity. |
| Large Hydropower | 11,250 MW | 1900MW exploited |
| Small Hydropower | 3,500 MW | 64.2 MW exploited |
| Solar | 4.0 $kWh/m^2/day$ – 6.5 $kWh/m^2/day$ | 15 MW dispersed solar PV installations (estimated) |
| Wind | 2-4m/s @10m height mainland | Electronic Wind Information System (WIS) available; 10 MW wind farm in Kastina state in progress. |
| Biomass (non-fossil organic matter) | -Municipal waste<br>-Fuelwood | -18.5 million tonnes produced in 2005 and now estimated at 0.5kg/capita/day.<br>-43.4 million tonnes/year Fuel wood consumption |
| | Animal waste | 245 million assorted animals in 2001 |
| | -Agric Residue<br>-Energy crops | -91.4 million tonnes/year produced.<br>-28.2 million hectares of arable land; 8.5% cultivated |

Source: Renewable Energy Master Plan (2013) and BP, (2017) Despite the abundance energy resources presented in Table 1.1, the access rate in Nigeria, is still around 45%, with the urban areas having greater percentage of the access, while the rural areas lack access with only about 30% connected to the grid (NREEEP, 2015). The average number of hours electric power is available to Nigerians is estimated at 6 hours daily (Ajao, et al, 2016). The industrial and household sectors alike, generate their own power using Gasoline, Natural gas and Diesel powered generators. These generators, emit harmful gases to the environment and are major sources of noise pollution especially in the densely populated urban areas and in rural areas where people live in clusters. Also, the demand for Premium Motor Spirit (PMS) and Diesel for private electricity generation especially in the household and business sectors are in competition with the demand for the products for transport, thereby causing artificial shortages in the system which always lead to hoarding of petroleum products and constant increase in the pump price of the products.

There have been attempts by the government towards solving this energy poverty issues, notable among them was the enactment of the ESPRA Act of 2005, which established the guidelines that led the successful unbundling of the defunct Nigeria Electricity Power Authority (NEPA) into 6 Generation companies (GenCos), 1 transmission company and 11 Distribution companies (DisCos). It established the Nigeria Electricity Regulatory Commission (NERC) which issues licences and regulates the electricity industry, the Nigeria Bulk Electricity Trader (NBET), which acts as an intermediary between the GenCos and Independent Power Producers (IPPs), through Power Purchase Agreements (PPA).

These efforts by the Nigerian government have been successful in adding additional generation capacities to the electricity grid. The total installed capacity of Nigeria at the end of 2017 stood at 12500MW, signalling a 171% increase to the installed capacity of the country in 2010 (Nigeria Electricity Hub, 2017). However, this increase is below the target set by Presidential Taskforce on Power in 2010 of having a total installed capacity of 40000MW by 2020.

**Table 1.2 Projected installed Electricity generation capacity by the Presidential Taskforce on Power, office of the Presidency, 2010**

| S/NO | Date | Hydro (MW) | Thermal (MW) | Total Installed capacity (MW) |
|---|---|---|---|---|
| 1. | July 2010 | 1230 | 3382 | 4612 |
| Short term | | | | |
| 2. | Dec 2010 | 1230 | 4149 | 5379 |
| 3. | April 2011 | 1380 | 5653 | 7033 |
| Medium term | | | | |
| 4. | Dec 2011 | 1575 | 8192 | 9767 |
| 5.<br>6. | Dec 2013 | 1775 | 12448 | 14218 |
| Long term | | | | |
| 7. | Dec 2020 | | | 40000 |

Source: Roadmap for Power Sector Reform, (2010)

Marching the set target as highlighted in Table 1.2, with the actual installed capacity as at 2017, it is observed that Nigeria have failed woefully in meeting its power generation target. As at April, 2017, the installed capacity of Nigeria stood at 12500MW (Nigeria Electricity Hub, 2017) while the production capacity at the end of 2017 stood at 7000MW (Sunday, 2018). This Figure, is even less than the target installed capacity for the medium term which ended in December, 2013.

Also, a look at the current installed generation capacity of Nigeria, shows that fossil fuel powered technologies dominate and is projected to still dominate over 90% of the installed electricity generation capacity in the future. Apart from large hydro power, renewable energy resource powered technologies were not allocated any share in the projected mix. However, in another projection by the Ministry of Power titled “National Renewable Energy and Energy Efficiency Policy (NREEEP)”, aimed at harnessing the country’s huge renewable energy potentials and making it part of the energy mix (see Table 1.3). Renewable energy powered technologies (excluding large hydro plants), were projected to contribute 362 MW to the total installed capacity of the country by 2015, but presently, there is no grid connected renewable energy powered technology (NERC, 2018). The renewable energy capacity addition target according to the National Renewable Energy and Energy Efficiency Policy (NREEEP) is presented below.

**Table 1.3: The renewable energy capacity addition target**

| S/NO | Resource | 2012 (MW) | Short term (2012) (MW) | Medium term (2020) (MW) | Long term (2030) (MW) |
|---|---|---|---|---|---|
| 1 | Hydro (LHP) | 1,938.00 | 2,121.00 | 4,549.00 | 4,626.96 |
| 2 | Hydro (SHP) | 60.18 | 140.00 | 1,607.22 | 8,173.81 |
| 3 | Solar | 15 | 117.00 | 1,343.17 | 6,830.97 |
| 4 | Biomass | - | 55.00 | 631.41 | 3,211.14 |
| 5 | Wind | 10 | 50.00 | 57.40 | 291.92 |
| | All renewables plus LHP | 1,985.18 | 2,438.00 | 8,188.20 | 23,134.80 |
| | All energy resources (on grid power plus 12,500MW of self-generated power) | 21200** | 24,380** | 45,490** | 115,674** |
| | % of renewables plus LHP | 23% | 10% | 18% | 20% |
| | % of RE less LHP | 0.80% | 1.30% | 8% | 16% |

Source: National Renewable Energy and Energy Efficiency Policy (NREEEP), (2015)

### 1.1.1 Rural Electrification in Nigeria

According to the National Renewable Energy and Energy Efficiency Policy of the Federal Ministry of Power (2015), 70% of the rural dwellers in Nigeria lack access to electricity. The federal government charged with the primary responsibility of ensuring a universal and undiscriminatory access to electricity has developed policies and institutions aimed at rural electrification but these have not yielded no significant result as the pace of rural electrification have failed to match the demand for electricity primary driven by population expansion. Some of the notable policies and institutions developed are highlighted below:

### 1.1.2 Policies to drive Rural Electrification in Nigeria.

#### 1.1.2.1 Nigerian Rural Electrification Programme (REP)

The REP was initiated by the Federal Ministry of Power and Steel (FMPS) in 1981 and was executed by NEPA. The policy had its major strategy of extending the national grid to connect the 774 Local Government Area Headquarters (LGAH) of the country. This resulted in greater access to electricity in 600 Local Government Area Headquarters and some fortunate consumers living very close to the area (Ohiare, 2014). However, the about 70% of rural households live without access to electricity (NREEEP, 2015).

#### 1.1.2.2 Federal Government of Nigeria (FGN) Rural Electrification Policy

The FGN's Rural Electrification Policy was developed in 2005, it outlines Government's objectives, goals, and policies concerning rural electrification. The RE Policy outlined the ideological framework guiding all rural electrification activities. The policy also outlines the roles and responsibilities of key Government agencies and provides guidelines for their cooperation and collaboration. The policy has one of its objectives as promoting cheaper, more convenient and more environmentally-friendly alternatives to the prevalent kerosene, candle, and vegetable oil lamps and fossil fuel-powered generating sets (Federal Ministry of Power, Works and Housing, 2015).

#### 1.1.2.3 The Rural Electrification Strategy and Plan (RESP) 2006 revised 2015

According to Federal Ministry of Power, Works and Housing, (2015), the Rural Electrification Strategy and Implementation Plan document was prepared using inputs from past works carried out by various rural electrification stakeholders in Nigeria. The strategy encourages more Public-private partnerships, where the private sector and community-based organizations will be increasingly responsible for much of the service delivery with minimum necessary financial support coming from the public sector. According to the policy document, "*While REA will set the general policy direction of RE activities, the development of projects themselves will come from the communities and operators that identify a particular need"* (Econ One, 2006).

#### 1.1.2.4 Rural Electrification Fund

In accordance with the EPSR Act 2005, the Rural Electrification Fund was established with objectives which include; achieving more equitable access to electricity across regions; maximizing the economic, social and environmental benefits of rural electrification subsidies; promote expansion of the grid and development of off-grid electrification; and Stimulating innovative approaches to rural electrification. The implementation encourages the combination of centralized and decentralized approaches and making use of all resources available at all levels of government.

### 1.1.3 Institutional developments towards rural electrification

#### 1.1.3.1 Energy Commission of Nigeria (ECN)

The Energy Commission of Nigeria (ECN) was established by Act No. 62 of 1979, as amended by Act No. 32 of 1988 and Act No. 19 of 1989. The commission is bestowed with the statutory mandate for the strategic planning and coordination of national policies in the field of Energy in all its ramifications. This made the ECN the apex government organ authorized to carry out overall energy sector planning and policy implementation, promote the diversification of the energy resources through the development and optimal utilization of all energy resources, including the introduction of new and alternative Energy resources like Solar, Wind, Biomass and Nuclear Energy to the energy mix of the country.

#### 1.1.3.2 Nigeria Electricity Regulatory Commission (NERC)

This commission was established based on the guidelines stipulated in the Electricity Power Sector Reform (EPSRA) Act, with a mission of promoting and ensuring an investor-friendly industry and efficient market structure to meet the needs of Nigeria for safe adequate, reliable and affordable electricity. NERC according to the EPSRA, is to act as a regulatory agency, overseeing the operations of the power sector in line with the following objectives:

- Uninterrupted electricity.
- Private sector participation.
- Consumer protection.
- Fair regulation.

#### 1.1.3.3 Federal Ministry of Power, Works and Housing

The power, works and housing ministry is a merger of three former separate ministries; power, works and housing. The power ministry is responsible for ensuring a robust power sector that supports the socio-economic needs of the country. Some of this function includes: Initiating and formulating broad policies and programmes on the development of the power sector in general and Implementing renewable energy programmes and initiatives.

#### 1.1.3.4 Nigeria Electricity Management Service Agency (NEMSA)

The agency was set up by the NEMSA ACT NO. 6 of 2015 to enforce technical standards, regulations, testing and certification of all the categories of electrical installations and appliances. This was a result of the experience the country had in the past with the use of substandard electrical equipment/material in the Nigerian Electrical Supply Industry (NESI) which have the tendency of causing disturbance in the power system and damaging some equipment used in power supply and in the operation of the real sectors of the economy

### 1.1.3.5 Rural Electrification Agency

The Rural Electrification Agency was established by the EPSR Act, the agency is saddled with the duty of ensuring the electrification of the rural and peri-urban areas in Nigeria with both renewable and non-renewable sources. It also acts as the intermediary between federal government, the states and local government areas. According to National Council on Power, (2014) extension of the national grid or providing off-grid solutions (mini grid and off-grid systems) for rural electrification using either fossil fuels or renewable energy powered technologies is the best solution for rural electrification.

### 1.1.4 Energy Access and Climate Change Nexus

There have been recent dilemma of providing affordable electricity and reducing the emissions from electricity generation. Emissions from electricity generation constitutes over 25 percent of the global Greenhouse gas emissions which is a major cause of climate change (EPA, 2017).

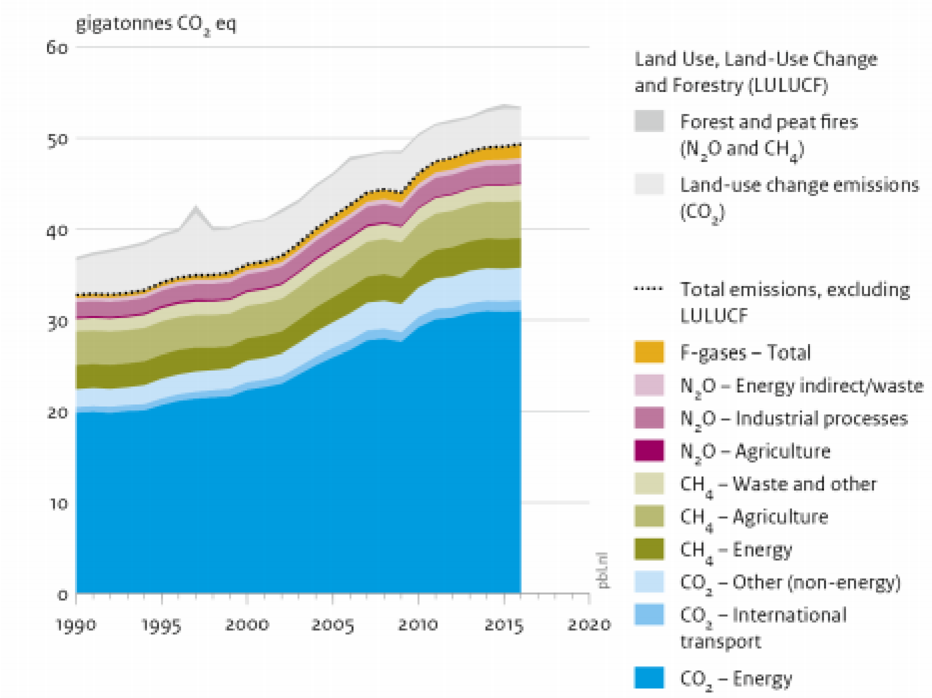



**Figure 1.1: Trend in Global Greenhouse Gas Emmissions Per Type of Gas and Sources**

Source: (Olivier, Schure , & Peters, 2017)

From Figureure 1.1, it is observed that growth in greenhouse gas emission maintained a study growth through 1990s to 2016, when the growth started increasing slowly by 0.5%, putting the total greenhouse gas emissions at about 49.3 gigatonnes of $co_2$ equivalent (excluding LULUCF). According to report, this is as a result of lower coal consumption and fuel swithches to natural gas and increased utilization of renewable energy powered technologies for power generation. $Co_2$ was identified as contributing over 65% of the total greenhouse gas emission and is mailnly from power generation and industrial processes excluding LULUCF.

Different roadmaps and targets through the Conference of Parties (COP) have over the years, been put in place to ensure that emissions from human activities are controlled so as to keep the earth temperature stable and habitable. These have led countries into setting targets to ensure that emissions especially from human activities which can be controlled are curtailed. Notable among these targets is the introduction of renewable energy technologies whose sources are cleaner with little or no emissions, into their electricity mix.

Studies have identified non-penetration of the renewable energy technologies especially solar and wind into the market as a result of their levelized costs which are still higher than the levelized cost of the fossil technologies (Budzianowski, (2017), Lazard, (2017, and Beltran, (2008). Budzianowski, (2017) opines that this cost disadvantage preventing a transition toward renewable energy is the failure to account for externalities associated with the use of fossil fuels in power generation. These are seen mostly in countries where the emissions from the convention fossil technologies are not charged, the emissions from these fossil fuel plant constitute externalities. In Nigeria, the uptake of renewable energy technologies has been on the increase, however, these uptakes have favoured more of the small sized off grid standalone systems mainly for complimenting the epileptic power supply from the grid. This is despite policies and institutions established to ensure increased rural electrification using Renewable Energy Technologies.

Therefore, in a bid to provide electricity access to a rural off-grid community and ensuring that carbon emissions into the environment are accounted for, this study provides an economic and environmental comparison of a Natural gas plant and Solar PV system utilizing a mini-grid.

## 1.2 Statement of Problem

Electricity access rate in Nigeria have been all time low, with approximate 70% of those living in the rural areas lacking access to the National electricity power grid (Federal Ministry of Power, 2015). These rural dwellers have over the years relied mostly on traditional burning of solid Biomass and private Gasoline Powered Generators for their energy needs, mainly for cooking, heating and lighting. These practice pose serious negative environmental and health effects.

The Rural Electrification Agency (REA) was established by Section 88(1) of the Electric Power Sector Reform Act (EPSRA) 2005, to promote and coordinate Rural Electrification in Nigeria. This led to the launch of National Rural Electrification Implementation Strategy and Plan of using both grid extension and off grid solutions (mini-grid and stand-alone systems) to support Rural Electrification projects. However, this has not brought any significant improvement to rural electrification in the country as about 70% of the people living in the rural areas are still without electricity. Presently, most project towards providing electricity to these rural off grid settlements have been on grid extension and with the privatization of the Power sector in 2013, the provision of electricity to rural off grid dwellers using decentralized systems is left in the hands of the private sector.

Also, with the recent dilemma of providing energy access and reducing environmental pollution, there is need to account for emissions involved with energy generation when providing energy access to the rural populace. Therefore, in a bid to increase rural energy access rate in Nigeria in line with the Sustainable Development Goal No. 7, this research work aims to provide an economic and environmental comparison of a mini-grid Natural gas fired plant and Solar PV system in Nigeria having Iyiora Anam Community as a case study.

## 1.3 Objectives of the study

The main objective of this study is to provide an economic and environmental comparison of a mini-grid Natural gas fired plant and Solar PV systems for electrification in Iyiora Anam Community. While the specific objectives are to:

1. Determine the cost of Electricity generation using Solar PV and Natural gas plant in Iyiora Anam Community.

2. The impact of emission charges on the cost of electricity generation using Solar PV and Natural gas plant in Iyiora Anam Community.
3. Conduct a sensitivity analysis of the impact of changes in some parameters on the cost of electricity generation electricity using each technology.

**1.4 Research Questions**

1. What is the cost of electricity generation using Solar PV and Natural gas plant in Iyiora Anam Community, Nigeria?
2. What is the impact of emission charges on the cost of electricity generation using Solar PV and Natural gas plant in Iyiora Anam Community?
3. How does changes in some parameters affect the cost of generating electricity using each technology?

**1.5 Rationale for the Study**

According to the Energy Led Growth theorists, energy plays a major role in the growth of any economy. It serves as a major factor input in the functioning of virtually all the sectors of an economy which cuts across: manufacturing, service, agriculture, education, health and transport sectors. Inadequate supply of energy impedes inclusive growth and development, it also adversely affects the quality of life of citizens, both in urban and rural areas. This strategic role energy plays in the growth and development of an economy, justifies why access to affordable, reliable, sustainable, and clean energy is assigned the goal No. 7 of the Sustainable Development Goals (SDGs).

Presently, there are few off grid projects aimed at rural electrification in Nigeria, these projects however are mostly; privately owned roof top solar PV systems and standalone diesel/gasoline powered generators. Investments in energy infrastructure have favoured the grid connected systems encouraged by the privatization of the power sector. This development has affected most rural communities living far from the existing grid as the economics of grid extension does not favour them.

Nigeria Electricity Regulatory Commission (NERC) (year) defined a rural area as an area situated over 10KM from the boundaries of an urban area or city, with less than 20,000 inhabitants and at least 20KM away from the nearest existing 11KV line.

Iyiora Ifite-Anam Community with about 829 households is located in Anambra west local government areas, Anambra State, Nigeria. The community is one of the communities living off the electricity grid in Nigeria as the existing 11KV line nearest to it in Nzam town is about 25KM away. The town is located near Igbariam axis of the OPL 917 within the Anambra basin, housing about 300 Billion Cubic Feet of Natural gas deposit (GEC Petroleum Development Company Limited, 2018). According to the data obtained from PVGIS, the area also has a favourable solar irradiance, at optimally inclined plane of average 5.45kWh/$m^2$, which is suitable for Solar PV. The need for electricity in this community is mainly for lighting, charging of phones, infotainment, cooling and minor commercial needs.

The inhabitant of the community who are predominantly farmers leave for their farms in the morning and return home in the evening. Through interactions with some of the villagers, they identified need for processing and storage of their farm produce which needs electricity. Presently their usage of electricity is mainly for lighting, charging of phones, infotainment, cooling and minor commercial needs which arise mostly in the morning and evening time therefore justifying the provision of a power system that will match their electricity demand as excesses cannot be sent to the grid.

Furthermore, this research which aims at an on-site economic assessment of the cost of providing electricity to Iyiora Anam community made use of real data instead of average countrywide data especially for the capital cost, maintenance cost, fuel cost, fuel transportation cost and other costs which are peculiar to the sites chosen and are likely to differ from other sites in different locations. The study also shows a sensitivity analysis of changes in some factors like fuel cost, emission charges and panel efficiency. This makes it easier for a prospective investor make an informed decision on the system to be deployed.

### 1.6 Scope of the study

The study sets to conduct an economic and environmental comparison of a Natural gas plant and Solar PV system for an off grid rural electrification in Nigeria. Due to limited time available for the research the study focused on Iyiora Anam community, in Anambra West Local Government Area which is an offgrid community, living 25km off the existing electricity grid in the region. The Levelized Cost of Electricity (LCoE), accounting for $CO_2$ emissions is utilized in the analysis.

## 1.7 Plan of the study

The structure of the study is organized as follows; chapter one is the introduction, where a brief background to the study, statement of the problem, objectives of the research, research questions, rationale for the study and the scope of the study is discussed. Chapter two provides the relevant literature review. Chapter three is for the methodology employed in fulfilling the specific objectives proposed in chapter 1. Chapter four is for the presentation, analysis of the result and discussion of the findings while Chapter five provides for the summary of the findings, conclusion and recommendations.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Introduction

This chapter discusses theories supporting emission charges in relation to the cost of electricity generation and other economic comparison theories, the different methodologies employed by various researchers on the subject as well as the empirical review of the existing literature on the subject.

## 2.2 Theoretical review

### 2.2.1 Market failure

According to the proponents of the general equilibrium analysis, competitive markets are efficient in the distribution of the factors of production leading to economically efficient outcome. This concept is regarded as a pareto efficient outcome which deals with achieving efficient resource allocation and redistribution in a competitive market system. An economy is said to be in a pareto efficient or optimal situation where it is making the best use of its resources in the production of goods and services. In this state, it is not possible to make one party better off without making someone else worse off. However, when a competitive market fails to redistribute resources efficiently, the market is said to have failed thus a creating a need for government intervention. According to Iwayemi, (2017), there are basically four explanations as to why market fail, these includes:

- **Market power:** The monopoly market outcome of lower output and higher price is Pareto inferior to the competitive outcome. This results to a deadweight loss due to the inefficiency of monopoly power.
- **Public goods:** A commodity is a public good if it satisfies two properties
  - It is non-excludable
  - It is non-rival

  Examples of public goods are national defence, police, fire protection, public TV and radio. When a commodity is non-excludable the free rider problem arises thereby making the marginal benefits of the consumers higher than their marginal costs.
- **Incomplete information**: one major assumption under a perfect competitive market, is that the Information is perfect and complete. However, when some economic

agents have more information than the others in engaging in economic transactions, it results to market failure.

- **Externalities:** when a production or consumption activity of an economic agent has an indirect effect or imposes a cost or benefit on the production or consumption activity of other agents usually a third letter.

### 2.2.2 Externality/ Social Cost Theory

William Kapp's theory of social costs has been a source of inspiration to modern ecological economists. According to Kapp, (1975) business firms fail to account for important social costs of production borne by third persons and future generations and as a result bring about a “serious deterioration of man's natural and cultural environment”. According to Mankiw, (2006), externality can be defined as the uncompensated impact of one person’s actions on the well-being of a third party/bystander. When this impact on bystanders is adverse it is regarded as negative externality but when the impact is beneficial, it is regarded as positive externality. Bhattacharyya, (2011), opines that if there is compensation or payment in return for damages, then the externality does not exist to the extent of compensation as it has been internalised. In other words, an externality is an unpriced, unintentional and uncompensated side effect of one agent’s action affecting another agent’s welfare (Bhattacharyya, 2011).

Baumol and Oates, (1988), in expanding the theory on economics and environment opined that economists see the problem of environmental degradation as one in which economic agents imposed external costs upon society at large in the form of pollution. And where there is no price to act as an incentive for reducing polluting activities, it results to excessive demands on the assimilative capacity of the environment. This increased activity and the effect it has on the environment imposes social cost on people. Bhattacharyya, (2011) argues that:

> *The existence of externalities creates a wedge between the private cost and the cost to the society. For any decision-making, economic agents rely on the private costs (i.e. costs borne by them). But when an economic activity generates an externality, the society bears the cost of its effects. As a result, the social costs are more than the private costs.*

Budzianowski, (2017), further defined external cost to include actual and real costs resulting from a process, but which are not included in the price of the product and therefore have to be paid by the public. Applying this definition to electricity, it shows that any cost resulting from electricity generation, distribution and consumption which is not included in the price of electricity constitutes an externality. This aspect of unaccounted cost especially in the generation of electricity is one of the major contributors of Greenhouse gases which has brought about climate change threats globally. These problems emerged from the start of the industrial revolution when the world's attention was on increased production of goods and services without much concern on the effects these actions have on the environment until the later part of the 20$^{th}$ century when environmentalists began call for reduction in carbon emissions.

However, there has been measures taken to reduce the occurrence of negative externalities associated with energy production and consumption, there is the direct control, which deals with imposing regulatory standards on the amount of pollution allowed. However, economists does not subscribe to this, because most production and consumption activities generate some negative externalities thus, the optimal pollution level is not zero (Iwayemi, 2017). The other approach is indirect which includes a variety of measures like: Imposition of tax on the polluter, creation of market for the sale of emission permits, tradeable permits and conferring property rights to one of the parties involved in the externality. Levinson and Shetty (1992) further classified the elements of pollution control system into three:

- **Behaviour control mechanism**: common alternatives which rely on regulation or incentives.
- **Level of control**: whether the instrument directly or indirectly influences the emissions;
- **Control variables**: Three important parameters here are price, quantity and technology. Quantity-based policies focuses on fixing the level of emissions allowed but allow prices to change. On the other hand, price-based policies focuses fix the cost of controlling emissions but allow the emission level to change in response to economic conditions. Technical solutions focus on fixing the technology level to generate an acceptable level of emissions.

**Table 2.1: Policies to reduce emissions**

| | | Price | Quantity | Technology |
|---|---|---|---|---|
| Incentive (economic) | Direct | Emission tax | Tradable emission permits | Technology tax on presumed emission |
| | Indirect | Fuel tax | Tradable production permits | Subsidize R&D, fuel efficiency |
| Non-incentive regulation | Direct | - | Emission standards | Technical standards |
| | Indirect | - | Product standards, bans, quotas | Efficiency standards |

Source: Levinson and Shetty (1992)

### 2.2.3 Carbon/Emission tax theory

According to Field and Olewiler, (nd), the most straightforward incentive-based approach to controlling emissions is to have the government or an agent of the government offer a financial incentive to change those emissions. This can be done in two ways: by taxing each unit of emissions, or by offering a subsidy for each unit of emissions that the source cuts back. In using the emission tax approach, the emitting entity is allowed to discharge any quantity of the taxed pollutant they wish provided they pay for every unit of discharge. The tax on emissions was popularised by Pigou, (1920) in explaining the role of taxes as a method of internalizing externalities, prompting environmental taxes to be regarded as Pigouvian taxes.

According to Glekman, (2014), carbon tax could reduce the risk of climate change by building emission costs into market prices of energy, hence discouraging the use of carbon-based fuels. Applying the concept of emission tax in the electricity sector, imposition of a tax requires the emitter to compare the cost of pollution reduction with the tax payment obligation. This arbitrage leads to a decision about whether it is worthwhile to abate pollution and up to a certain level or to pay tax for emissions. The polluter will choose an option depending on the cost-benefit.

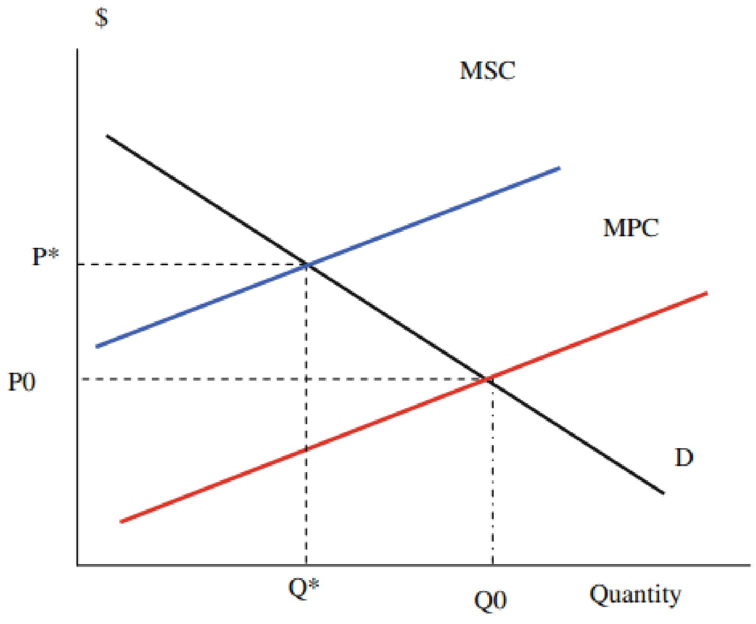



**Figure 2.1: internalizing social cost**
Source: Bhattacharyya, (2011)

From Figure 2.1, an electricity supplier in a competitive market will consider only the private costs of supplying electricity to consumers. The supplier will set the equilibrium quantity (kWh) to Q0, whereas the quantity considering the social cost of supply is Q*. Correspondingly, the price will be P0 but when emission tax is considered, the price per kilowatt-hour increases to P*. This process of reaching the quantity supplied in presence of an externality is called internalisation of externalities. At P*, electricity is sold at the price where the social cost borne by the society equals the private cost to the producer. At this point, a perfect comparison can be made by an electricity producer from a wide range of technologies (fossil powered technologies and renewable energy powered technologies), in order to make a choice as to which technologies will offer the best profit. This comparison involves a wide range of economic tools which forms investment decision metrics. This includes; Net Present Value (NPV), Levelized Cost of Electricity (LCoE) analysis and Life Cycle Analysis (LCA).

### 2.2.4 Net Present Value (NPV)

This is evaluated by subtracting the present value of periodic cash outflows from the present value of periodic cash inflows. Net Present Value measures the present-value of money exclusive of inflation. The NPV approach (also referred to as discounted cash flow (DCF) approach) uses the time value of money to convert a stream of annual cash flow generated by a project to a single value at a chosen discount rate. Budzianowski, (2017), argues that this approach also allows one to incorporate income tax implications and other cash flows that may vary from year to year. The discounted cash flow or net present value method takes a spread of cash flow over a period of time and "discounts" the cash flow to yield the cumulative present value. When comparing alternative investment opportunities, the NPV is a useful tool. In making investment decisions, the project with the highest cumulative NPV is the most attractive one. NPV is obtained by subtracting OPEX from the total annual income ($I_N$), discounting it by dividing by $(1+p)^N$, summing up over all project years, and subtracting CAPEX from it. This is shown in equation (2.1).

$$\text{NPV} = \sum_{N=1}^{N=L} \frac{I_N - OPEX_N}{(1+p)^N} - CAPEX \tag{2.1}$$

Where:

OPEX= Operational expenditure.

$I_N$, = total annual income at year N

P = the discount rate

$(1+p)^N$ = the discount factor

n = the project's economic life in years.

CAPEX = capital expenditure

One serious limitation with the NPV approach is that it should not be used to compare projects with unequal time span making it not suitable to be used in this analysis. Monocrystalline Silicon Solar PVs have a life span of about 15 years while Micro turbine has a life span of 50 years. Therefore using the NPV as a measure of choosing between the two technologies will be misleading and projects with longer life span will have a higher positive NPV than the one with a shorter life span.

### 2.2.5 Levelized Cost of Electricity (LCoE)

Levelized Cost of Electricity (LCOE) analysis is an assessment tool usually used to value the cost of electricity generation at plant or broader levels, in order to compare them with expected electricity sales revenues, to see if the technology can breakeven (Lucheroni and Mari, 2016). Thus, LCOE is the implied price ($/kWh) of energy generated by a power system. Budzianowski, (2017), defines it as the minimum price needed to break-even. LCOE provides power system investors with a standard tool for measuring the cost of electricity over the life span of a power plant and also helps them compare electricity cost across a wide range of technologies (Ueckerdt et al., 2013). This approach takes care of the life span difference limitations associated with the use of NPV approach for power investment analysis as any system which generates electricity at a lower levelized cost is the most economically feasible. The LCOE model can be reconstructed in different ways to ensure it matches research tasks and data availability. This variation was done by Lazard, (2017) in a comparative analysis (levelized cost of energy) across various technologies in the United States. However the standard formula for calculating the levelized cost of a power investment is

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (2.2)$$

x

where:

LCOE = the average lifetime levelised cost of electricity generation

$I_t$ = CAPEX in the year $t$

$M_t$ = OPEX in the year $t$

$F_t$ = fuel expenditures Foster, in the year $t$

$E_t$ = electricity generation in the year $t$

$r$ = discount rate

$n$ = economic life of the system.

Foster, Wagner and Bratanova, (2014), in presenting some variations to the standard LCoE framework used in many countries like the United States, California, United Kingdom and Australia, reports that *"the theoretical framework for all the reviewed models as well as for other LCoE based research are similar in foundation, with only differences in the calculation stages, some variables and assumptions used".*

One limitation of the LCoE approach is that it does not account for energy price escalation. This makes it possible for a project whose levelized cost is lower than the current electricity tariff to become cost competitive when electricity tariff is increased. Also a plant which uses fossil fuel may lose its price competitiveness when fuel prices increases in the future. However with the introduction of future markets for fossil fuels and Power purchase agreements for power generators, this limitation may no longer constitute a serious threat to making investment analysis. Also, for an investor who wish to rely on the spot market for fuel supplies, some software like Homer have been developed to allow these investors perform sensitivity analysis of the effects of fuel price variations on the prices of electricity especially with fossil fuel resources whose price may change at any time due to some factors affecting their demand and supply.

### 2.2.6 Life Cycle Analysis (LCA)

According to Kannan, (2007), Life Cycle Analysis is a cradle-to-grave approach in analysing an energy system in its entire life cycle. This is considered in three phases viz. construction, operation and decommissioning. The construction phase, includes the manufacturing of the plant equipment and on-site construction of the plant. The operational phase involves fuel use during the entire operational lifetime and upstream process of fuel production. While the decommissioning phase, involves demolition of energy system, disposal and recycling of materials used in the construction (Kannan, 2007).

Budzianowski, (2017), argues that in analysing a power system, if the factors involved in, or resulting from them system process are analysed comprehensively and to the full lifetime of the process and its consequences, the study is called a ‘life cycle analysis’. For example, for a wind turbine, life cycle analysis would include the manufacture of components from recycled metal and from the mining of metallic ores, the environmental impact of such mining, and that of other materials, manufacture, per unit factory construction and maintenance, energy supplies in construction, decommissioning. One major advantage of this method over the LCOE method and other methods discussed earlier is that it analysis Greenhouse gas emissions other than those at the power plant and other environmental impact (Turconi and Astrup, 2014).

However, Kannan, (2007), LCA only accounts for environmental implications and does not account for economic implications. Also, Budzianowski, (2017), maintains that reducing the analysis to quantifiable amounts for mathematical analysis requires common units, which are often money, “but in practice, only significant influences are included. Usually, there is debate about what these are and how they are valued and quantified, e.g. visual impact, assessed perhaps by change in local house prices, or employment, assessed perhaps by cancellation of unemployment entitlement”. This approach however, is not employed for analysis in this research work as the available time frame is not sufficient for gathering data on manufacturing of the components, onsite installations, upstream process of fuel production, fuel transport and their decommission. The comparison is based only on the operational phase of the power plants as regards fuel use and power generation during the entire operational lifetime.

### 2.3 Empirical Review

This section presents empirical studies on the various objectives of the research. From the available literature reviewed, it was discovered that several studies on the impact of emission charges on the Levelized Cost of Electricity have been conducted and concluded. These findings are based on actual observations and measured phenomena unlike theoretical review that is based on theories and beliefs. However, they focused more on country wide data, thereby neglecting some specific data which can affect investment decisions by private investors.

#### 2.3.1 The cost of electricity generation using solar PV and natural gas plants.

The cost of electricity generation has favoured the fossil fuel powered technologies over the years. The result of the Levelized Cost of Electricity (LCoE) comparison done across different technologies by Tarjanne and Kivisto, (2008) in Finland, shows that Nuclear power had the lowest LCoE at €0.035/kWh, followed by Peat powered technologies at €0.0436/kWh, Coal at €0.0457/kWh, Natural gas (CCGT), at €0.0512/kWh, Wind at €0.0529/kWh and Wood at €0.0736/kWh. Also, a look at the comparison done in 2008 in Mexico by Beltran, (2008) across nine different technologies using Levelized Cost framework shows that CCGT plants has the least levelized cost at $0.07/kWh, Nuclear plant at $0.074/kWh, Coal at $0.076/kWh, Geothermal 0.08/kwh, Oil powered plants at $0.087/kwh, Hydro at $0.091/kWh, wind at $0.093/kWh, CT plant at $0.117/kWh and GT plants having the highest levelized cost at $0.137/kWh.

Recently, the renewable energy powered technologies have experienced a continuous decline in their levelized cost. This was supported by Energy Innovation, (2015) in accessing the levelized cost of some wind and solar technologies. The results of their analysis show that the average cost of onshore wind fell from $135 per megawatt-hour in 2009 to $59 in 2014 signalling a 56 percent drop in five years. The cost of utility-scale photovoltaic technology also fell from $359 per megawatt-hour in 2009 to $79 in 2014, showing a 78 percent decline. Also, a look at the result of Lazard, (2017), comparison across electricity generation technologies in the United States, it is observed that renewable energy technologies has become cost competitive with the fossil powered technologies. The result from this study shows that wind energy has the lowest levelized cost at $0.03/kWh, followed by Combined Cycled Gas Turbine (CCGT) at $0.042/kWh, Solar PV (thin film utility scale) at $0.043/kWh, Solar PV (crystalline utility scale) at $0.046/kWh, Biomass at $0.055/kWh, Micro turbine at $0.059/ kWh, Coal at $0.06/kWh, Gas Reciprocating Engine at $0.068/kWh, and Solar PV (roof top), at $0.085/kWh.

From this, it is observed that renewable energy technologies (excluding Solar PV roof top), have become competitive over fossil fuel technologies even when deployed on a smaller scale. This decrease in LCoE of renewables can be attributed to technological advancement in some countries due to extensive research and development.

Also factors other than technological advancement like cost of labour, tariffs, taxes and interest rates can be factors leading to variations in LCoE across countries making it pertinent for an investor who which to invest in any country to carry out an independent assessment of the country and location of the project for investment decisions rather than relying on assessments done in other countries or cities. For instance, IRENA, (2012), carried out an analysis on wind powered technologies across the different continents of the world. From the result, LCoE for onshore wind was the lowest in China and India, ranging from $0.06 to $0.11/kWh, followed by North America at $0.07 to $0.11/kWh and Europe at $0.08 to $0.14/kWh.

The discrepancy in the LCoE electricity can be seen in the case of Nigeria, where a similar study was carried out in 2017, by the Nigerian Economic Summit Group and Heinrich Böll Stiftung, Nigeria. The result of the analysis, shows that for on-grid systems, at Weighted Average Cost of Capital (WACC), at 11%, large hydro plants have the lowest LCoE, estimated at $0.041/kWh, followed by CCGT plants at $0.061kWh. OCGT plants at $0.07/kWh, Solar PV at $0.13/kWh and Wind (onshore) at $0.13/kWh. For off grid systems, Natural gas fired plants had the lowest LCoE at $0.095/kWh, followed by small hydro plants at $0.10/kWh, solar PV at $0.19/kWh and Diesel at $0.21/kWh.

### 2.3.2 The competitiveness of solar PV and natural gas plants when emissions are accounted for

According to Budzianowski, (2017), one major reason why fossil fuels may currently have a cost advantage over renewables is because most analysis are based solely on market prices, that “if externalities are included several renewables would likely become the most affordable energy sources in particular onshore wind, geothermal, and biomass energy”. The author went further to compare the cost of electricity generation in 2020 using traditional fossil fuel methods and various renewable alternative in European Union when emission costs are accounted for. The result of the analysis shows that the renewable energy technologies such as Solar PV, Concentrated Solar Power and Offshore wind became cost competitive only after emissions involved in electricity generation using fossil fuels were accounted for.

Similarly, Tarjanne and Kivisto, (2008), compared the Levelized Cost of Electricity (LCoE), across different technologies in Finland and the result shows that Nuclear powered plants has the lowest LCoE at €0.035/kWh, followed by Wind powered technologies at €0.0529/kWh, Natural gas (CCGT) plants at €0.0592/kWh, Coal at €0.0644/kWh, Peat at €0.0655/kWh and Wood at €0.0736/kWh.

Some studies, also used the Life cycle cost analysis method to compare the cost per kWh of different technologies. Kannan, et al, (2007), for Singapore, utilized the life cycle assessment (LCA) and life cycle cost analysis (LCCA) methodology, which is a cradle-to-grave (construction, operation and decommissioning) approach, to analyse an energy system in its entire life cycle. The result shows that CCGT plants have the lowest life cycle cost, estimated at $0.05/kWh, followed by Orimulsion fired steam turbine plants at $0.07/kWh, Oil fired steam turbine plants at $0.075/kWh and mono-crystalline solar PV at $0.28/kWh (at solar PV system cost of Singaporean $6.5/W). This analysis gives a proper assessment of systems as their entire life cycle vis components manufacturing, installation, fuel transport, system operations and decommissioning. However, for investment purpose the investor is only concerned with the cost the business is likely to bear and which is mostly on the operation of the plants thereby justifying the choice of LCoE analysis in this research work, taking into account the Carbon emissions from the operations of the system.

### 2.3.3 Sensitivity analysis of the impact of changes in some factors on the competitiveness of each technology.

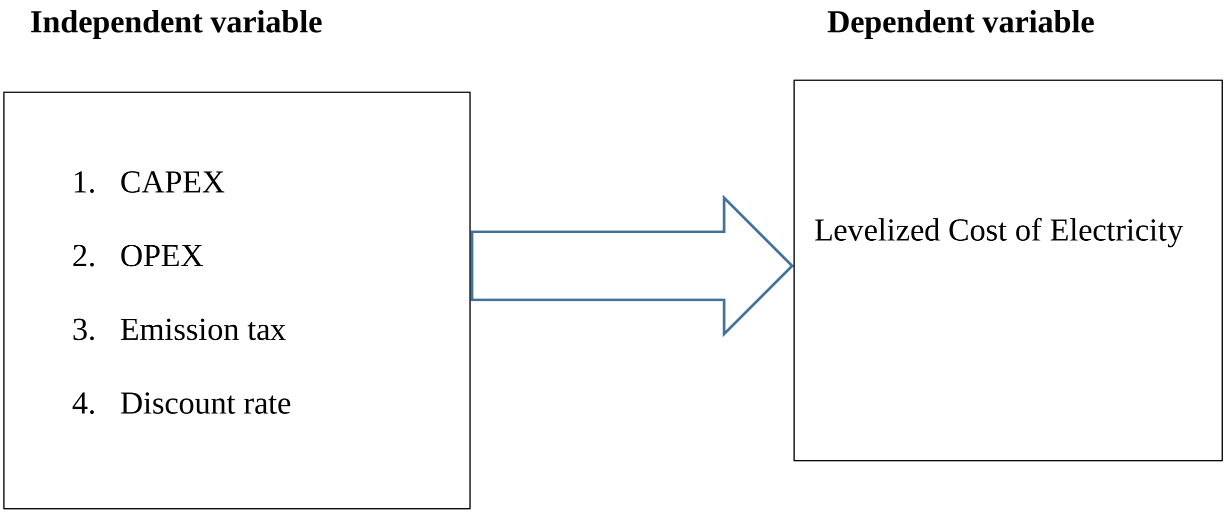
Based on the criticism of the LCoE as not being able to account for price of fuel escalation and other variations in cost makes it important to check for the likely effects those changes may have on the cost of electricity generation across technologies. Nigerian Economic Summit Group and Heinrich Böll Stiftung, (2017) compared across different generation technologies and conducted a sensitivity analysis to check how the variations in emission tax (\$40/$tco_2e$, \$60/$tco_2e$, and \$100/$tco_2e$) will impact on the cost of grid connected electricity systems in Nigeria. The results show that at \$40/$tco_2e$, Hydro powered plants have the lowest SCoE estimated at \$0.041/kWh, followed by CCGT plants at \$0.07/kWh, OCGT plants at \$0.08/kWh, Wind onshore at \$0.09/kWh, Nuclear at \$0.1/kWh, Solar PV at \$0.1/kWh, Biomass at \$0.115/kWh, Coal at \$0.15/kWh and Concentrated Solar Power (CSP) at \$0.20/kWh.

At \$60/$tco_2e$, Hydro powered plants have the lowest SCoE estimated at \$0.041/kWh, followed by CCGT plants at \$0.08kWh, Wind (onshore) at \$0.085/kWh, OCGT plants at \$0.09/kWh, Nuclear plants at \$0.1/kWh, Solar PV at \$0.1/kWh, Biomass at \$0.115/kWh, Coal at \$0.17/kWh and CSP at \$0.20/kWh.

At \$100/$tco_2e$, Hydro powered plants also have the lowest SCoE estimated at \$0.041/kWh, followed by Wind (onshore) at \$0.085/kWh, Nuclear plants at \$0.1/kWh, Solar PV at \$0.1/kWh, CCGT plants at \$0.11kWh, Biomass at \$0.115/kWh, OCGT plants at \$0.12/kWh, CSP at \$0.20/kWh and Coal at \$0.21/kWh.

Taking a clue from these variations, it can be seen that the choice of a technology for electricity generation investment should accommodate many factors especially in the wake of the continuous call for reduction in global emissions making countries charge carbon emitters a tax for each unit of carbon resulting from their activities. Also, with the volatility in price of fossil fuels, efforts should be made to perform a proper analysis before settling for any technology to avoid suppling energy at a price the consumers may not be able to afford.

## 2.4 Conceptual Framework




## 2.5 Summary of Literature review and Gaps

From the literature reviewed, it is observed that cost of electricity generation vary across regions. This can be attributed to quality of the resource available, the technology used in converting it to electricity, labour costs, taxes, interest rates among others. The cost of electricity generation using fossils can also be affected by emission costs, it is observed that as emission cost increases, the renewable energy powered technologies become more competitive over the fossil powered technologies. Electricity generation cost is also affected by the economics of scale. This is always seen to be in favour of mostly large scale grid connected technologies against the off grid systems because the cost of storage to cover for intermittent sources of the renewable energy technologies usually used in off grids systems contributes to the cost.

Furthermore, it is observed that none of the research works reviewed, attempted an environmental assessment of an off-grid system in addition to the economic assessment. Also, the analysis were not site specific. This study therefore, attempts to fill this gap in knowledge, utilizing an on-site economic and environmental comparison of Natural gas plant and Solar PV technologies in Iyiora Community, in Anam town, Anambra West L.G.A. of Nigeria.

CHAPTER 3

# METHODOLOGY

## 3.1 Introduction

This chapter discusses the methodology adopted for the study. It is divided into sections: Section 3.1 is the introduction, 3.2 discusses the study area, 3.3 is the preference of the study area 3.4 gives overview of the theoretical framework, section 3.5 presents the estimation technique, section 3.6 shows the System design Components while section 3.7 describes the data sources

## 3.2 The Study area


Figure 3.1: The study area

Source: HomerPro (2018)

Iyiora is a rural community in Ifite-Anam town, located in Anambra West Local Government Area of Anambra State, Nigeria. The town lies between Latitude $62^0$26.1'N and Longitude $66^0$32.0'E. The community occupies a surface area of about $1KM^2$. comprising of 829 households. It is bordered by Ifite Anam to the East, Nmiata Anam to the West and Aguleri to the South, Omambala River to the North. The town is located 25KM away from Nzam where the existing distribution grid network is located. The inhabitants of the community are predominantly farmers who specialized in fishing and cultivation of crops like Rice, Yam, Cassava and Vegetables. A small portion of villagers specialize in petty trading, handcrafts while the rest are Artisans. The community has administrative and social infrastructure like Village Hall, Health Centre, Church, Primary School and Secondary School. All these activities require electricity.

### 3.3 Preference of the study area

The energy situation in Iyiora Ifite-Anam is like most remote rural African communities living in the South of Sahara. The community with about 829 households and has been without grid connected electricity, most households rely on gasoline powered generators for their electricity need, the hospital depend on the Roof top Solar PV installed for them in 2012 for some of their electricity needs. The town is located near Igbariam axis of the OPL 917 within the Anambra basin, housing about 300 Billion Cubic Feet of Natural gas deposit (GEC Petroleum Development Company Limited, 2018). The area also have a considerate level of sunshine estimated at Annual Average of 4.81kWh/m$^2$, suitable for the deployment of Solar PV. For the past three years there have been increased economic activities in the area as a result of the construction of Iyiora Anam Bridge over the Omambala River which cuts the town off from the other towns in the region. Due to the location of the town (25KM off the existing grid network), extending the grid network to them may not be feasible as they stay more than 20km off the existing grid network in the area. The community live in a clustered setting, an observation made in other communities in the Local Government Area, making it easy and cost effective for a mini grid system to be deployed in the area, as a five (5) minutes' walk from one end of the village is sufficient to get the other end of the village.

### 3.4 Theoretical Framework

To undertake an economic and environment assessment of Natural gas and Solar PV System, this study adopts the theoretical framework of Levelized Cost of Electricity (LCOE) analysis. This cost allows investors compare the cost of generating one kilowatt-hour (kWh) of electricity from different generation technologies with varied capital costs, fuel costs and lifespans. This framework provides an assessment tool used to assess the cost of electricity generation over the life span of a power plant in order to compare them with expected electricity sales revenue, to see if the technology can breakeven (Lucheroni and Mari, 2016). It is also called Bus-bar cost. The standard LCOE model as was proposed by Short, Packey and Holt, (1995) is presented below:

$$LCOE = TLCC \div \{\sum_{n=1}^{N} [Q_n \div (1 + d)^n]\}$$

Where:

LCOE = levelised cost of energy

TLCC = total life-cycle cost (comprises of Capital and operational expenditures)

$Q_n$ = energy output or saved in year n

d = discount rate

n = analysis period.

Also, the LCOE model can be reconstructed in different ways to ensure it matches research tasks and data availability. Lazard, (2017) in a comparative analysis (levelized cost of energy) across various technologies in the United States reconstructed the model to account for carbon emissions from power plants. Foster, Wagner and Bratanova, (2014), in presenting some variations to the standard LCoE framework used in many countries like the United States, California, United Kingdom and Australia, reports that the alterations to the standard LCoE model are only in the calculation stages due to the nature of variables and assumptions used but their foundation are similar.

### 3.5 Method of Estimation

To arrive at a proper economic and environmental assessment between Natural gas and Solar PV plants for an off grid rural electrification in Iyiora Anam, some input data such as the load profile of the community (peak load and base load), solar irradiance of the location, Natural gas supply price, cost of the Solar PV panel, cost of the Balance of Systems such as (Batteries, Inverters), cost of Micro Turbine and its components, Natural gas supply cost, interest rates, life time of systems etc were sourced. These data serve as data input for LCoE model in Homer Pro software. The software is used for simulating different systems for optimal choice for microgrid and other distributed electrical power systems. It also help in conducting sensitivity analysis to check for the impact of changes in some factors will have on the performance of the system. For this study, parameters like fuel (natural gas) price, emission charges and annual average solar irradiance were varied to analyse further their effects on the cost of generating electricity for the two systems.

## 3.6 Design Components and Parameters.

### 3.6.1 Solar PV module

In this study the 295Watts Solar PV panel consisting of 60 Monocrystalline Cells were selected. A Panel costs about US$230 with an average life span of 25 years based on the information supplied by African Sustainable Energies Nig Ltd, an energy company which specializes in Sales, Installation and Maintenance of Solar systems in Nigeria.

The initial capital cost of solar energy (plus Installation costs ) for of 1 kW solar energy systems were found to be US$ 780 and the replacement cost was also considered equal cause it is considered that the entire unit will be replace in case of replacement. Annual O&M cost is estimated at US$20.

**Component specifications**

| | |
|---|---|
| Technology: | Mon-crystalline (Mono) |
| Dimensions: | 65.00 x 39.10 x 1.57 inches |
| Cell Arrangement: | 60 (6x10) |
| Nominal Maximum Power (Pmax): | 295 Watts |
| Module Efficiency: | 18.02% |

### 3.6.2 Power Inverter

Since the current produced by Solar PV Panels are Direct Current (DC), there is need to convert it to Alternating Current (AC) for use by home appliances. Costs of inverters and control chargers vary according to their sizes. For this study, PRETL REFUsol48k model of inverter is selected. The average lifetime of the inverter is 10 years. For a 1 kW of converter the system initial and replacement cost was considered to be US$ 288 (plus installation). The technical specifications of this inverter are shown below.

**Components specification**

| | |
|---|---|
| Rated Power | 5.5 k VA / 5.0 Kw |
| Max. Power at 25°C for 1 hour | 40 kW |

| | |
|---|---|
| Nominal Voltage | 400V |
| Efficiency Inverter peak efficiency | > 98.2% |

### 3.6.3 Storage Batteries

Generally, batteries are used for energy storage purpose, to store excess power from renewable energy systems necessary to meet power demand when cannot generate enough power. For this study, the storage battery selected is the Kinetic Battery It has dual case replaceable cells and an expected life of over 10 years. The selected battery has the following characteristics. The capital cost of the selected battery was taken to be US$ 300, with a maintenance cost of US$ 15/ year.

| | |
|---|---|
| Nominal capacity | 260 Ah (3.11 kWh) |
| Maximum charge current | 43A |
| Efficiency | 80 % |
| Nominal voltage | 12 (V) |
| Capacity ratio | 0.563/ hr. |

### 3.6.4 Micro turbine

Recuperated micro turbines with recuperated units using sheet-metal heat exchanger that recovers some of the heat from an exhaust stream and transfers it to the incoming air stream, thereby boosting the temperature of the air stream supplied to the combustor was used. The turbine has an efficiency of 30%, a capital cost of US$950/kW (turbine and installation) costs. The operation and maintenance cost $0.010 per kWh.

### 3.6.5 Interest rate

The interest rate used for this analysis is 15%.

### 3.6.6 Inflation rate

An annual average inflation rate of 10% was used. The Figure was derived from the historical inflation rate data and projects for Nigeria.

### 3.6.7 Natural Gas Price

The price of Natural gas with the transportation to the site was estimated at US\$0.45/$M^3$. US\$0.37/$M^3$T US\$0.40/$M^3$ and US\$0.47/$M^3$ were used for the sensitivity analysis and were obtained by varying the cost of gas transportation and taking the average of the historical price changes.

### 3.6.8 Carbon price

The price per ton of CO2 was estimated at US$20.23 based on the European Carbon market price. US$21 and US$22 were employed for the sensitivity analysis.

### 3.6.9 Average Annual Solar Irradiance

Annual Average (kWh/m$^2$/day) Solar Irradiance for the location is 4.81/kWh/m$^2$/day. The figure was varied to 4.00/kWh/m$^2$/day, 5.00/kWh/m$^2$/day and 8.00/kWh/m$^2$/day was used for the sensitivity analysis.

## 3.7 Source of Data

Data on the electricity demand estimate of the community was gotten from Rural Electrification Agency of Nigeria, Solar irradiance was gotten from Homer Pro software by inputting the coordinates of the location. Natural gas supply cost was gotten from NIPCO NIG LTD, a downstream CNG supplier in Nigeria, the cost of Solar PV Panels and the Balance of System was gotten from African Sustainable Energies Nig Ltd, an energy company which specializes in Sales, Installation and Maintenance of Solar systems in Nigeria., cost of Micro Turbine and components was gotten from Saratoga Energy Resources, an Energy Equipment Marketing, Sales and Maintenance company in Nigeria. Interest rate for loan was gotten from African Sustainable Energies Nig Ltd. The interest rates are majorly from foreign investors since the ones offered by Nigerian commercial banks are very high. The Average Annual Solar irradiance was gotten from HomerPro while the carbon price was gotten from Business Insider, a website for $CO_2$ European emission allowances.

# CHAPTER FOUR

# RESULTS AND DISCUSSIONS

## 4.1 Introduction

This chapter deals with the presentation, analysis of the result and discussion on the findings. This chapter is divided into several sections: section 4.1 deals with the introduction, section 4.2 deals with result presentation, section 4.3 deals with result analysis, while section 4.4 discusses the results of the analysis.

## 4.2 Result Presentations

### 4.2.1 Community Load Profile

The information gathered on the activities of the inhabitants of Iyiora Anam is presented in Figure 4.1 below. From the Figureure, it is seen that their electricity consumption is more at night and less in the morning.

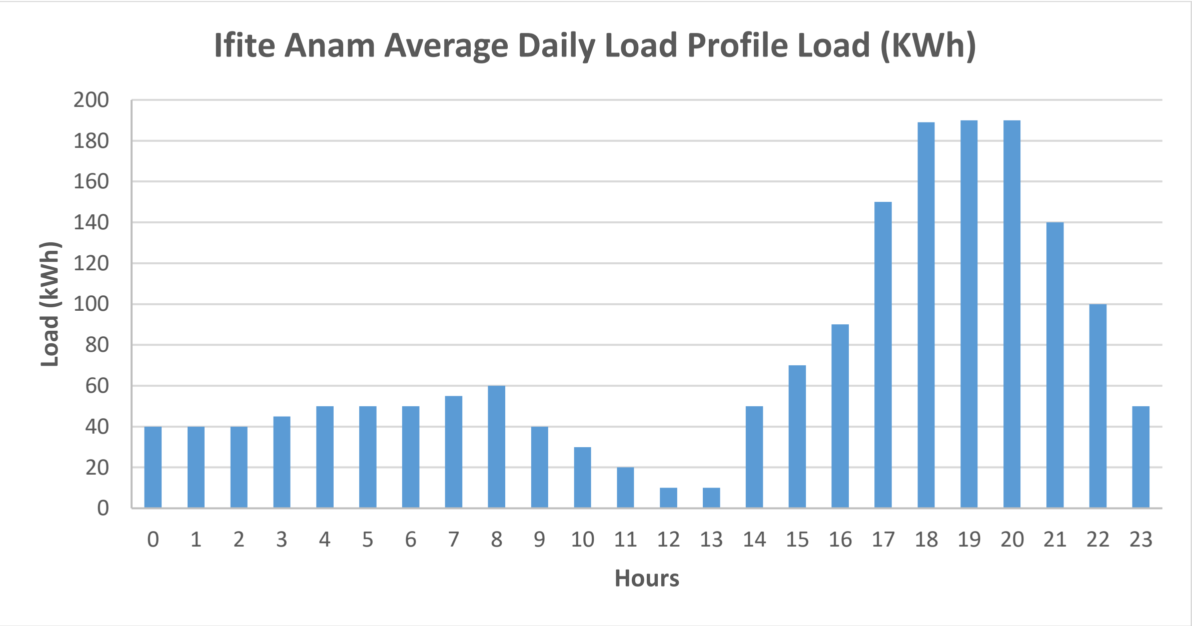



Figure 4.1: Ifite Anam Average Daily Load Profile Load (KWh)

Source: Authors computation from HomerPro data

The average daily load profile of Ifite Anam in Figure 4.1 shows that the community load does not exceed 60kWh between 23hours in the midnight and 14hours in the afternoon. This is because, the inhabitants are at sleep or away in the farms during these periods. It is also observed that during the morning hours, there is little demand for electricity as many households are preparing to set out to their farms. The demand is mostly for lighting and other usage mostly from Hospitals, Commercial Centres and Schools. From 15hours, when the school children return back from school, their mothers also return home to take care of the kids and prepare dinner along with the female grown up children, the load starts increasing. The peak load is witnessed between 17 hours and 21 hours when other members of the family return home from farms and businesses. The usage of power for infotainment, lighting, ironing or clothes for the school children take place to drive the load to 190kWh between 18hours and 20hours. The demand starts decreasing from 21hours as people retire to their beds. The cycle begins again the next day.

### 4.2.2 Levelized Cost of Electricity in Iyiora Anam.

The result of the Levilized Cost of Electricity in Anam for a Natural gas powered Micro Turbine and a Solar PV system are presented in Table 5.1 below. This cost takes into consideration; the Capital costs of the system, the operation and maintenance costs, Variable operational and maintenance costs.

**Table 4.1: Cost of Electricity generation in Iyiora Anam**

| **Cost Component** | **Solar PV (US$)** | **Natural gas micro turbine (US$)** |
|---|---|---|
| Total Net Present Cost | 3,377,050.00 | 4,550,287.00 |
| Capital Cost | 2,123,137.83 | 214,500.00 |
| Operating Cost | 84,958.73 | 237,151.20 |
| Operating and Maintenance Cost | 586,096.39 | 1,681,651.52 |
| Fuel Cost | 0.00 | 1,987,531.91 |
| LCoE | 0.3567 | 0.3876 |

Source: Author's computation from data in HomerPro

Table 4.1 gives a cost breakdown of the cost of electricity generation in Iyiora Anam using Solar PV and Natural gas powered micro turbine. Natural gas micro turbine has a higher Total Net Present Cost estimated at US$4,550,287.00 while Solar PV has a Net Present Cost of US$ 3,377,050.00. For Natural gas micro turbine, the main driver of the cost is the operating expenditure which covers the Operating costs, Operation and Maintenance costs and the fuel cost. The solar PV system has lower operating expenditure with low operating costs, low O&M costs and no Fuel cost. It has a very high capital cost which comprises; cost of the Panels, cost of Battery storage and cost of Inverters. The capital cost of the Natural gas turbine (cost of turbine, transport and installation costs) is about 10% of the cost of the Solar PV system.

However, the Levelized cost of generating electricity with the two systems shows that Solar PV has a lower levelized cost of US$ 0.3567 while the levelized cost of electricity using natural gas micro turbine at US$ 0.45/m$^3$ of gas is US$0.3876. The cost breakdown of the two systems are presented in the chart below.

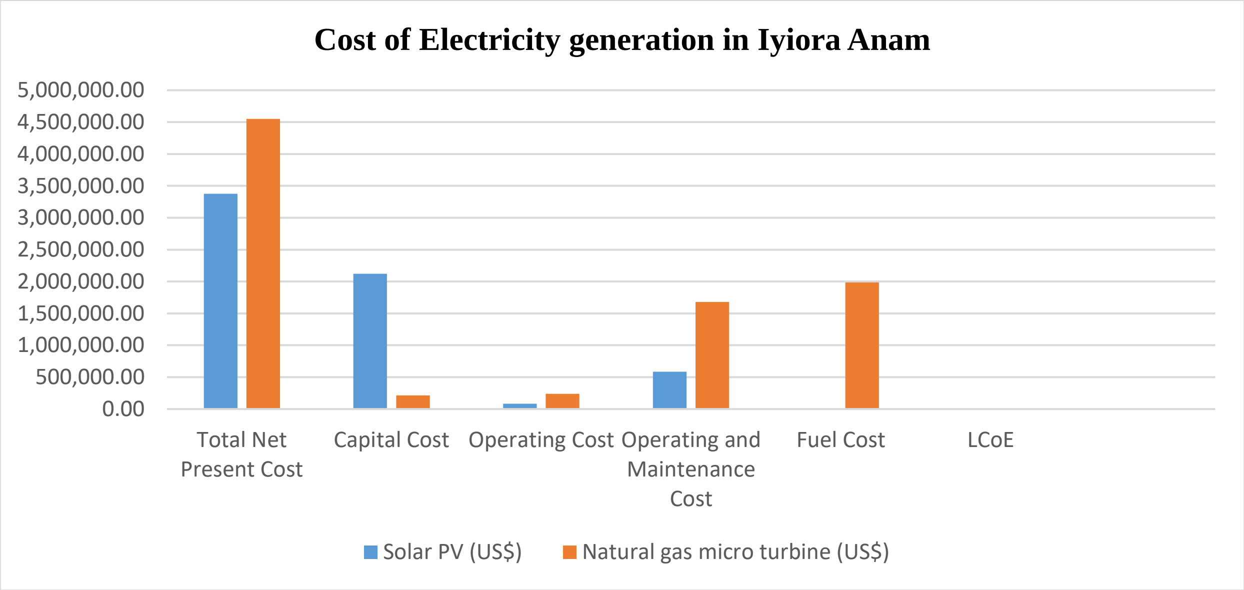



Figure 4.2: Cost of Electricity generation in Iyiora Anam

Source: Author's computation from data in HomerPro

### 4.2.2 Impact of emission cost on the levelized cost of electricity generation in Iyiora Anam

The table below shows the impact of emission cost on the levelized cost of electricity generation in Iyiora Anam. Here the emission cost per ton of $CO_2$ is estimated at US$20.26.

**Table 4.2 Impact of emission cost on electricity generation in Iyiora Anam**

| **Cost Component** | **Solar PV (US$)** | **Natural gas micro turbine (US$) without emission cost** | **Natural gas micro turbine (US$) with emission cost** |
|---|---|---|---|
| Total Net Present Cost | 3,377,050.00 | 4,550,287.00 | 4,723,050.00 |
| Capital Cost | 2,123,137.83 | 214,500.00 | 214,500.00 |
| Operating Cost | 84,958.73 | 237,151.20 | 246,600.70 |
| O&M Cost | 586,096.39 | 1,681,651.52 | 1,854,414.58 |
| Fuel Cost | 0.00 | 1,987,531.91 | 1,987,531.91 |
| LCoE | 0.3567 | 0.3876 | 0.4024 |

Source: Author's computation from data in HomerPro

The result of the analysis presented in Table 4.2 shows how cost of carbon emissions affect the cost of electricity generation in Iyiora Anam. At US$20.26, the Total Net Present Cost (NPC) of the natural gas powered plant rose to US$ 4,723,050.00 from US$ 4,550,287.00, which was the NPC when emissions were not accounted for. The cost did not affect the capital cost as it does not depend on fuel consumption rather on the cost of the system, transport and installation costs. The operation and maintenance costs rose from US$1,681,651.52 to US$1,854,414.58 as a result of the emission cost per kilogram of $CO_2$ payable by the investors for the emissions from their natural gas plants. The levelized cost per kWh of electricity increased form US$0.3876 to US$0.4024 as a result of the emission charge of US$23.26 per kilogram of $CO_2$ emitted from the natural gas plant. The result of the analysis is presented on the chart below.

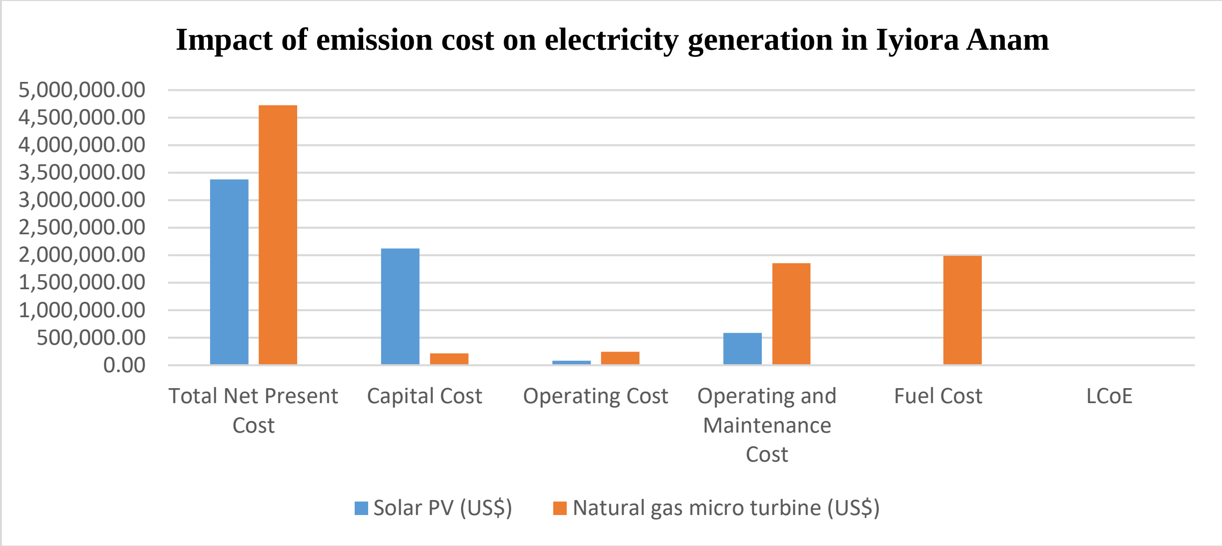



**Figure 4.3: Impact of emission cost on electricity generation in Iyiora Anam**

Source: Author's computation from data in HomerPro

### 4.2.3 Sensitivity of the levelized cost of electricity generation to variations in some factors in Iyiora Anam

To arrive at a proper investment decisions some important parameters like fuel (natural gas) price, emission charges and solar irradiance were varied to analyse further the sensitivity of the levelized costs of the systems to these changes of these parameters. The results are presented below.

**Table 4.3 Sensitivity of cost of electricity generation to fuel price variations in Iyiora Anam**

| **Cost Component** | **US$.370/m$^3$** | **US$ 0.400/m$^3$** | **US$ 0.45/m$^3$** | **US$ 0.47/m$^3$** |
|---|---|---|---|---|
| Total Net Present Cost | 4,196,948.00 | 4,329,450.00 | 4,550,287.00 | 4,638,622.00 |
| Capital Cost | 214,500.00 | 214,500.00 | 214,500.00 | 214,500.00 |
| Operating Cost | 217,824.90 | 255,072.20 | 237,151.20 | 241,982.80 |
| Operating and Maintenance Cost | 1,681,651.52 | 1,681,651.52 | 1,681,651.52 | 1681651.52 |
| Fuel Cost | 1,634,192.91 | 1,766,695.03 | 1,987,531.91 | 2,075,866.67 |
| LCoE | 0.3575 | 0.3688 | 0.3876 | 0.3952 |

Source: Author's computation from data in HomerPro

From Table 4.3, it is observed that price (US$/m$^3$) of natural gas has a positive relationship with the LCOE. As the price of natural gas increases, the levelized cost of generating electricity increases. This increase also affect the Total Net Present Cost, operating cost and the total fuel cost. When the price of natural gas was US$.370/m$^3$ the levelized cost was estimated at US$ 0.3575. Similarly, when the gas price increased to US$ 0.400/m$^3$, the LCOE increased to US$0.3688. As the price of natural gas rose to US$ 0.45/m$^3$, LCOE increased to US$0.3876 and further to US$0.3952 when the price of natural gas was increased to US$ 0.47/m$^3$. This result of the analysis is also presented on the chart below:

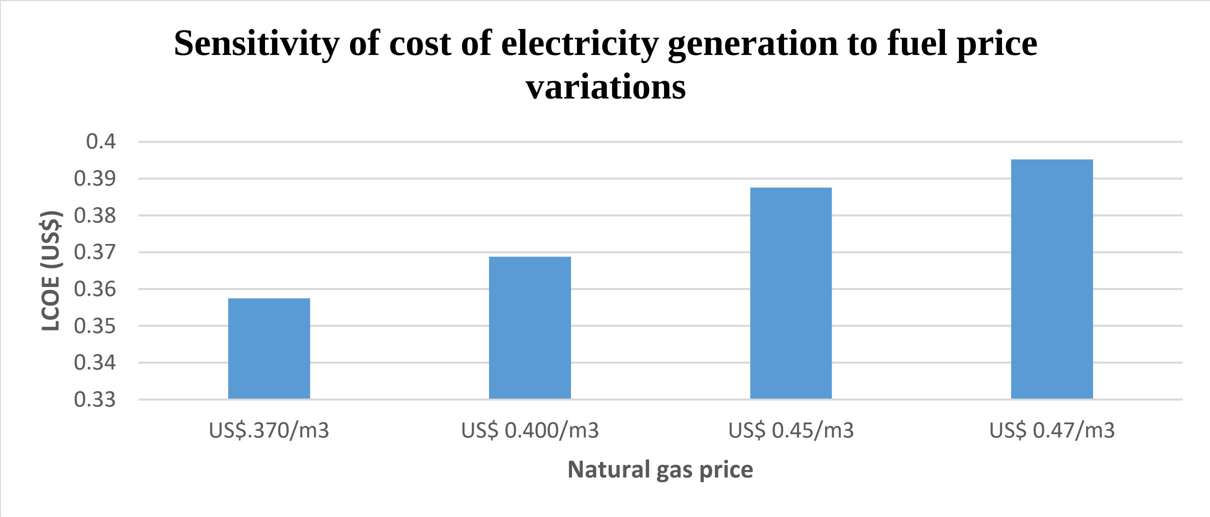



**Figure 4.4: Sensitivity of cost of electricity generation to fuel price variations in Iyiora Anam**

Source: Author’s computation from data in HomerPro

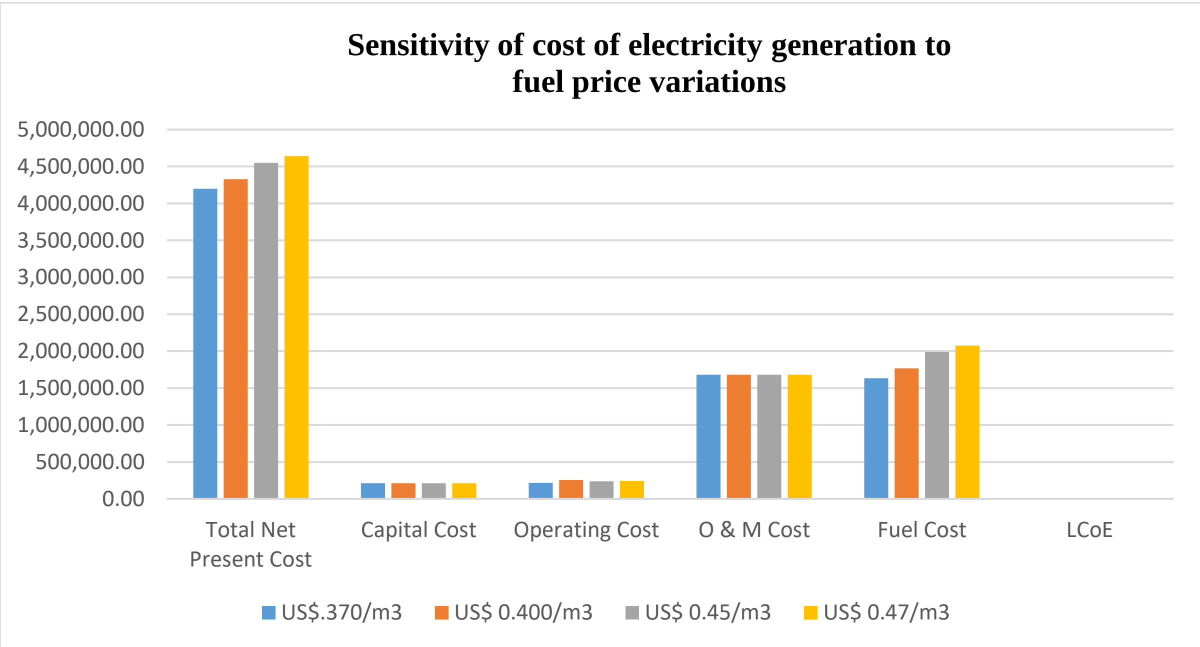



Figure 4.5: Sensitivity of cost of electricity generation to fuel price variations to in Iyiora Anam

Source: Author’s computation from data in HomerPro

**Table 4.4: Sensitivity of cost of electricity generation to the variations in Emission charges in Iyiora Anam**

| **Cost Component** | **US$20.26/ton of $CO_2$** | **US$21/ton of $CO_2$** | **US$22/ton of $CO_2$** |
|---|---|---|---|
| Total Net Present Cost | 4,723,050.00 | 4,729,360.00 | 4,737,888.00 |
| Capital Cost | 214,500.00 | 214,500.00 | 214,500.00 |
| Operating Cost | 246,600.70 | 246,945.80 | 247,412.20 |
| Operating and Maintenance Cost | 1,854,414.58 | 1,860.724.78 | 1,869,252.08 |
| Fuel Cost | 1,987,531.91 | 1,987,531.91 | 1,987,531.91 |
| LCoE | 0.4024 | 0.4029 | 0.4036 |

Source: Author's computation from data in HomerPro

Table 4.4 shows how variations in emission price, is likely to affect the cost of generating electricity in Iyiora Anam. The variables also exhibited positive relationship just like that of the fuel price with the LCOE and other cost components. From the result of the analysis obtained from HomerPro, when emission price is increased from US$20.26/ton of $CO_2$ to US$21.00/ton of $CO_2$ the Net Present Cost increased to US$4,729,360.00 from the initial value of US$4,723,050.00. Further increase of the NPC to US$4,737,888.00 was witnessed when the emission charges was raised further to US$20.26/ton of $CO_2$. The changes in the other cost components like the operating and maintenance cost due to the variation in the emission charges were also witnessed. However, the emission charges does not affect the capital cost which comprises; the procurement, transport and installation costs of the system.

The levelized cost of electricity (LCOE), exhibited a similar trend with the NPC. When the emission charges was US$20.26/ton of $CO_2$ the LCOE was US$0.4024, when the emission price was set at US$21/ton of $CO_{2,}$ the LCOE in Iyiora Anam rose to US$4029. When the price of emission increases to US$22/ton of $CO_{2,}$ the levelized price also increased in the same direction to US$0.4036. The result is also presented in the chart below:

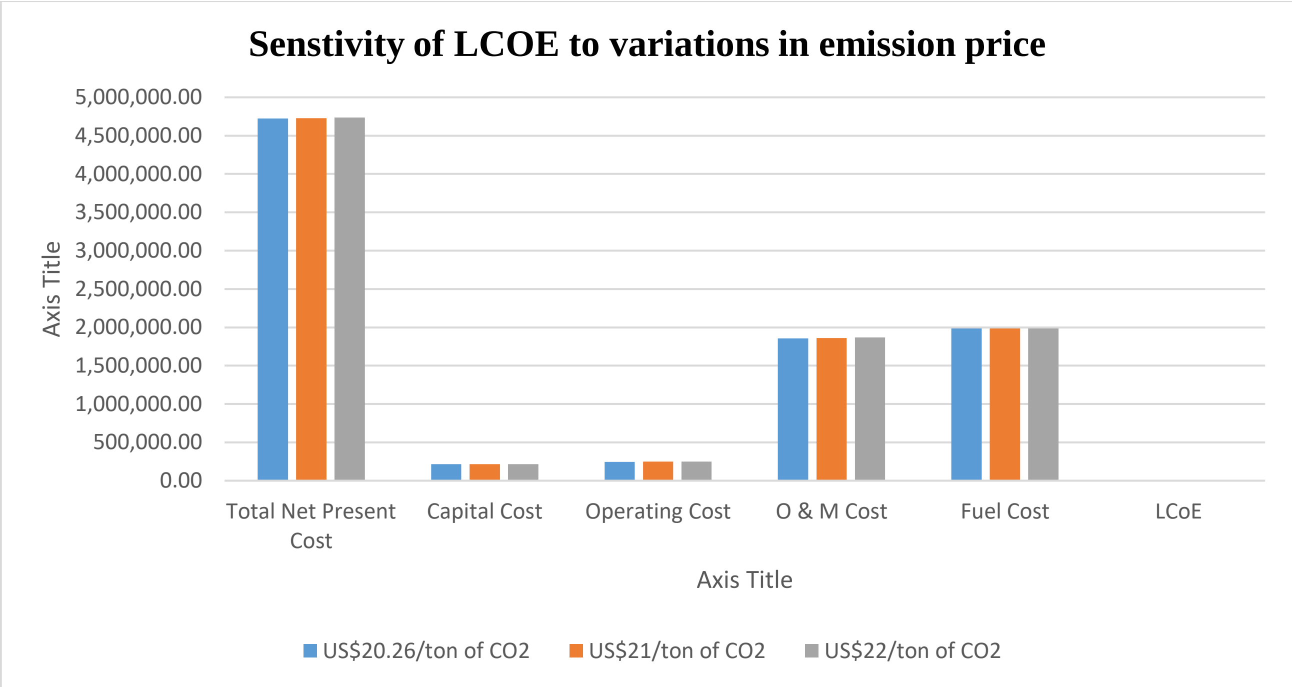



**Figure 4.6: Senstivity of Costs of electricity generation to emission price variations in Iyiora Anam**

Source: Author's computation from data in HomerPro

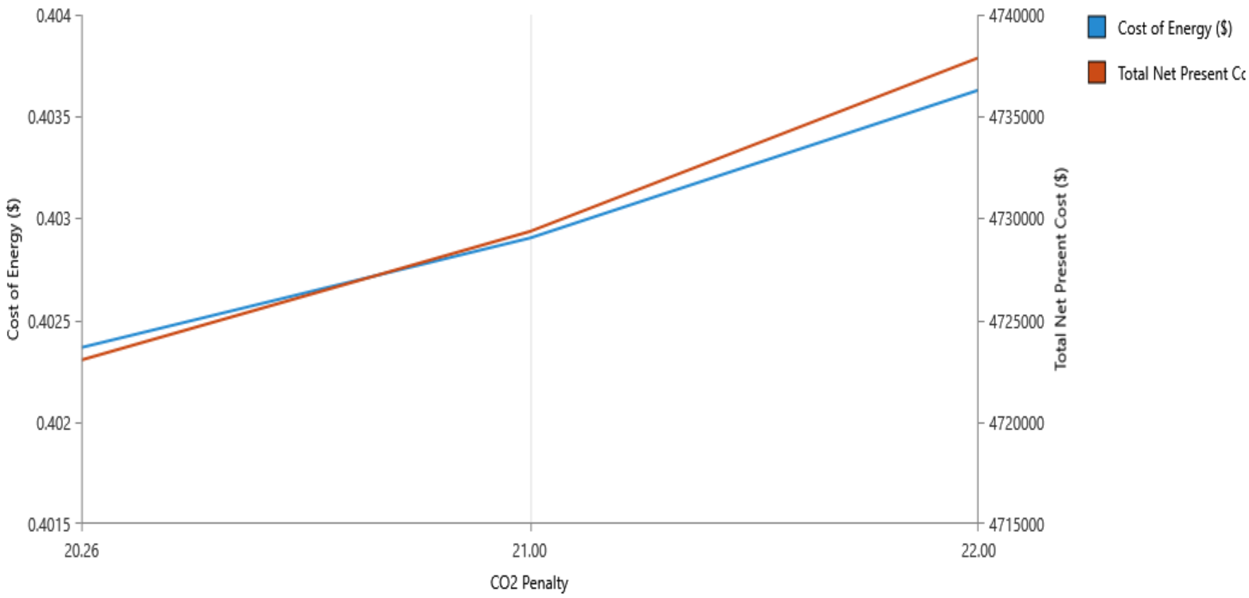



**Figure 4.7: Sensitivity of LCOE to emission price variations in Iyiora Anam**

Source: Data output from HomerPro

**Table 4.5: Sensitivity of cost of electricity generation to Annual Average Solar irradiance variations in Iyiora Anam**

| Cost Component | 4.00/kWh/m$^2$/day | 4.81/kWh/m$^2$/day | 5.00/kWh/m$^2$/day | 8.00/kWh/m$^2$/day |
|---|---|---|---|---|
| Total Net Present Cost | 3,715,240.00 | 3,377,050.00 | 3,382,149.00 | 3,577,376.00 |
| Capital Cost | 2,423,339.38 | 2,123,137.83 | 2,123,455.52 | 2,374,596.63 |
| Operating Cost | 87,532.62 | 84,958.73 | 85,282.66 | 81,494.16 |
| O & M Costs | 674,167.41 | 586,096.39 | 580,078.47 | 632,077.50 |
| Fuel Cost | 0.00 | 0.00 | 0.00 | 0.00 |
| LCoE | 0.3924 | 0.3567 | 0.3573 | 0.3779 |

Source: Author's computation from data in HomerPro

Table 4.5 presents the sensitivity of cost of electricity generation to changes in Annual Average (kWh/m$^2$/day) Solar Irradiance in Nigeria using 4.81/kWh/m$^2$/day which is the Annual Average Solar Irradiance of the location as the base. The analysis shows that a higher and lower Annual Average (kWh/m$^2$/day) Solar Irradiance decreases the quantity of electricity generated using a Solar PV, thus increasing the whole components of the cost of generation. When Annual Average (kWh/m$^2$/day) Solar Irradiance is reduced to 4.00kWh/m$^2$/day, the capital cost increased from US$ 2,123,137.83 to US$ 2,423,339.38, the operating and maintenance cost also increased from US$ 586,096.39 to US$ 674,167.41. The increase of these costs increased the Net Present Cost to US$ 3,715,240.00 from US$ 3,377,050.00. An increase in the Annual Average (kWh/m$^2$/day) from 4.81kWh/m$^2$/day to 5.00kWh/m$^2$/day indicates slight changes in the cost components which include the levelized cost of electricity. However, a further increase of the Annual Average (kWh/m$^2$/day) to 8.00kWh/m$^2$/day indicates significant increase to the electricity generation cost components of the system. The capital cost increased to US$2,374,596.63 from US$2,123,137.83, the O&M Costs increased from US$ 586,096.39 to US$ 632,077.50. These increases drove the Net Present Cost and Levelized costs to US$ 3,577,376.00 and

US$0.3779 from the initial costs estimated at US$ 3,377,050.00 and US$0.3567 respectively. The result of the analysis is presented on the charts below.

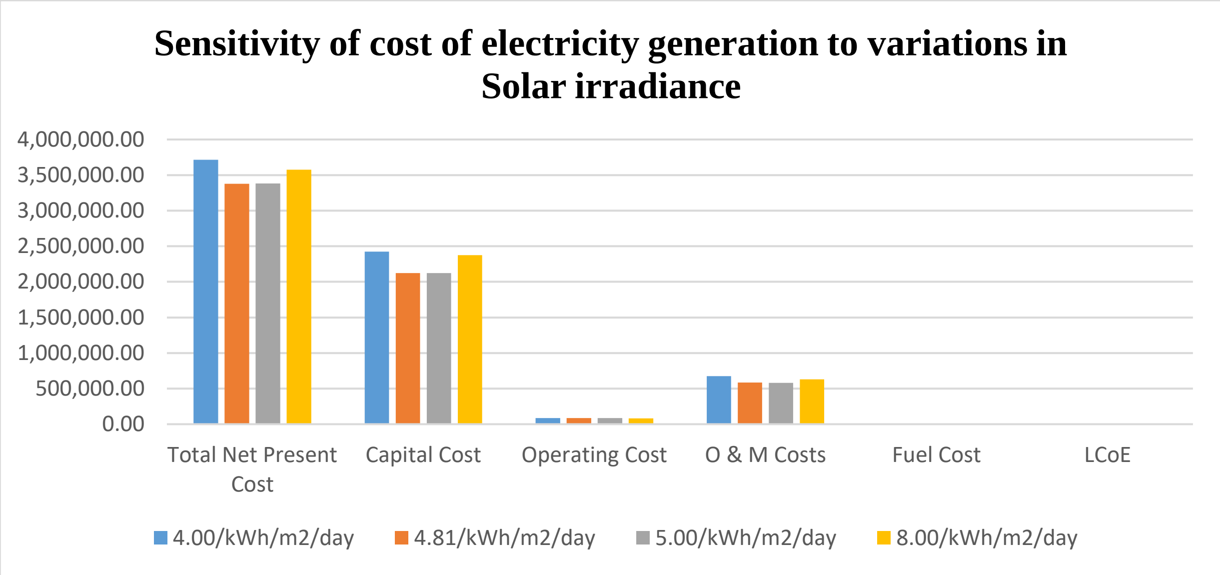



**Figure 4.8: Sensitivity of cost of electricity generation to Annual Average Solar irradiance variations**

Source: Author's computation from data in HomerPro

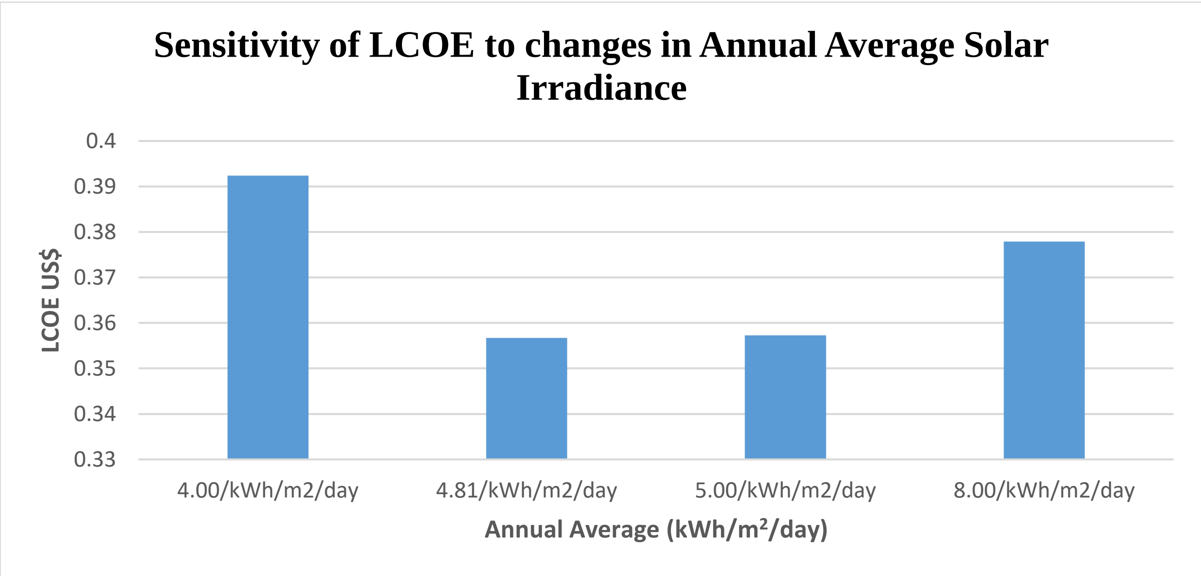



**Figure 4.9: Sensitivity of LCOE to changes in Annual Average Solar Irradiance**

Source: Author's computation from data in HomerPro

### 4.3 Comparison of Results

The results of the analysis of this study are compared below with similar studies which has done a comparison between the natural gas plants and solar PV plants for offgrid electrification. Also, it goes further to compare the analysis with other studies on the impact of emission charges on the cost of electricity generation and how variations in some cost components of the systems affect the LCOE.

For the first objective, which is to find the cost of electricity generation using Solar PV and Natural gas powered micro turbine, it is observed that Solar PV have a higher upfront capital cost than the Natural gas plant. The system has no fuel cost since solar energy is free and ubiquitous compared to natural gas which costs US$0.45/m$^3$ (resource and transport cost). Also, Solar PV has a lower operation and maintenance cost, a lower levelized cost of electricity and a lower Net present cost (Total cost adjusted to the current period). This view is supported by Nigerian Economic Summit Group and Heinrich Böll Stiftung, (2017) except for their reported levelized cost of electricity Figure which indicates that Natural gas plant has a lower levelized cost compared to off grid solar PV systems. However, the study is not site specific may not be same for all locations.

Also, the cost components showed variations between the two systems. For example, the capital cost for the Natural gas plant is just about 10% of the Solar PV system. This cost according to Budzianowski, (2017), forms one of the reason why penetration of renewable energy has not been widespread. Investors with limited funds may be discouraged from investing in Solar PV systems despite having a lower levelized cost. However the levelized cost gotten from the analysis is higher than the price per kilowatt of grid electricity in Nigeria for residential customers. Distribution companies in Nigeria sell power at US$0.08/kWh to residential class of consumers and selling electricity at a higher price than that bought by their counterparts in the city may affect the viability of the project despite Rural Electrification Agency's permission for Mini-grids with capacity under 1 MW to set cost-reflective tariffs.

The impact of the emission charges on the cost of electricity generation in Iyiora Anam was conducted to address the second specific objective. The result also showed that when emission costs are accounted for, the cost components of the natural gas plant increases. Nigerian Economic Summit Group and Heinrich Böll Stiftung, (2017) reported a similar result for an on-grid comparison but at a US$100/t$co_2$e. From the available literature reviewed, studies for an off grid cost comparison accounting for emission are not available. Nigeria presently does not charge for $co_2$ emissions from electricity generation. This may be because there is still a huge power supply gap in the country, so most policies are for incremental power supply from both fossils and renewable energy sources.

For the sensitivity analysis of the effect of changes in the cost of some variables on the cost of electricity generation in Iyiora analysis, it was observed that fuel cost have a significant contribution to the cost of electricity generation. This cost affect all the components of the operational expenditure. As the cost of natural gas increases, the cost of electricity increases too. Lazard, (2017) reported that increase in the fuel cost has a direct positive relationship with the cost of generating electricity in the analysis across different electricity generation technologies for the United States. For the sensitivity of the electricity generation cost to the variations to the cost of emissions it was also discovered that cost of electricity generation and emission charges move in the same direction. This view was also upheld by Nigerian Economic Summit Group and Heinrich Böll Stiftung, (2017) where at different charges per ton of $CO_2$ emitted into the atmosphere, the levelized cost of electricity move in the same direction.

For the variation in the annual average solar irradiance, it was discovered that a Solar PV system does not perform better in a higher or lower average solar irradiance. The system performs better when the average annual solar irradiance is between 4.50 to 5.00kWh/$m^2$/day. This view is supported by Barron-Gaffird, et al (2015) and Padden, (2017) who introduce the concept of "voltage drop" to explain the concept which opines that power is a product of voltage and current (P= V * I), temperature increases only the current but decreases the rest state of the electron within the solar cell.

# CHAPTER FIVE

# SUMMARY, CONCLUSION AND RECOMMENDATIONS

## 5.1 Introduction

In this chapter; summary of the findings of the study, the conclusion and policy recommendations to promote sustainable rural electrification are presented.

## 5.2 Summary of Findings

This research work aims at an Economic and environmental comparison of a natural gas plant and Solar PV systems for rural electrification in Nigeria with a case study of Iyiora Anam, Nigeria. The specific objectives are to determine the cost of electricity generation using Solar PV and Natural gas plant in Iyiora Anam Community, the impact of $CO_2$ emission charges on the cost on the cost of Solar PV and Natural gas plant in Iyiora Anam Community and to conduct a sensitivity analysis of the impact of changes in some parameters on the cost of generating electricity with each technology. Site specific data were used to carry out the analysis using HomerPro software for simulating different systems for optimal choice for microgrid and other distributed electrical power systems.

The results of the analysis show that Solar PV has a lower levelized cost but a higher Capital cost 90% higher than the Natural gas plant which has a lower capital cost but a higher levelized cost of electricity. When emission cost were modelled into the Natural gas powered system, its levelized cost increased further to show the uncompensated impact generating electricity with Natural gas will have on people and the environment by extension. Also, a sensitivity analysis to assess the likely effect variations in some parameters like fuel cost, emission charges and annual average solar irradiance will have on the cost of electricity generation on the site was done. The results show that fuel price and cost of electricity generation have a positive relationship, also emission charges and the cost of generating electricity exhibited a positive relationship. However, the annual average solar irradiance were discovered to have varying relationship with cost of electricity generation, as higher or lower average solar irradiance reduces the performance of the Solar PV system thus leading to a higher cost of electricity generation.

The implication of these findings for Iyiora Anam is that Solar PV system is a preferred technology for its electrification. Also, to other off grid communities in the area, solar PV will be a preferred technology for their electrification. However their high capital (upfront) costs may be a hindrance towards adoption.

### 5.3 Conclusion

The importance of energy in the growth and development of a country cannot be overemphasized. This importance of energy to the functioning of virtually all sectors of an economy made it occupy an important position in the Sustainable Development Goals as Goal No. 7. In Nigeria, access to electricity which is the most widely used form of energy is very low as the access rate is below 50% with about 70% of the population living in the rural area not having access to the grid supply electricity. With the privatization of the power sector generation and distribution of electricity has been left to the private sector.

This study in a bid to ensure access to electricity for the rural offgrid communities while protecting the environment, performed an economic and environmental comparison between a Solar PV and Natural gas plant in Nigeria with Iyiora Anam as a case study. The result of the analysis favoured the Solar PV system as it has a lower levelized cost of generating electricity which is a better comparison model than the Net Present Value analysis and other methods as it allows for projects with different lifespans to be compared and the model modified to suit the needs of the analyst.

### 5.4 Recommendations

Based on the findings of the empirical analysis, the following policy options are necessary to improve rural electrification in Nigeria.

- Despite the Rural Electrification Agency's allowance for Minigrids under 1 MW to set cost-reflective tariffs, there is need for the government to develop policies which will further ensure that power system components (Panels, Batteries and Inverters) are subsidized so as to enable private investors have confidence in investing their fund in the offgrid areas especially for solar which have a high capital cost. These policies are important because apart from the known costs used in analysing energy projects, decisions about electricity supply project are also risk-based. This risks like construction issues, power price issues and climate change may affect the project thereby encouraging investor to go for projects with lower capital costs like that of Natural gas powered systems.

- The interest rate for off grid power projects should be reviewed to a single digit to encourage investors who wish to participate in the off grid segment of the Nigeria power industry. The interest rate offered by the commercial banks are high going up to 27% and this increases the Net Present Cost and make the levelized cost much higher than the grid supplied electricity thereby discouraging investment in offgrid electrification projects.
- Increased electrification in Nigeria have favoured the fossil powered systems despite their environmental impact revealed from the result of the analysis. Therefore, the federal government should introduce policies aimed at discouraging $CO_2$ and other Greenhouse gas emissions form electricity generation. Policies like emission tax per ton of $CO_2$ and emission allowance should be promoted so as to ensure that the externalities involved in the generating electricity using fossil fuels are compensated.
- Finally, Efforts should be intensified in promoting the adoption of more Solar PV systems in the rural electrification strategy of Nigeria due to its low operation and maintenance costs. Solar PV remains the most viable option among all renewable energy sources in Nigeria as the country has a considerable annual average solar irradiance across all locations. Increased adoption is expected to further reduce the cost of the components and the cost of electricity generation by extension.

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# Appendix

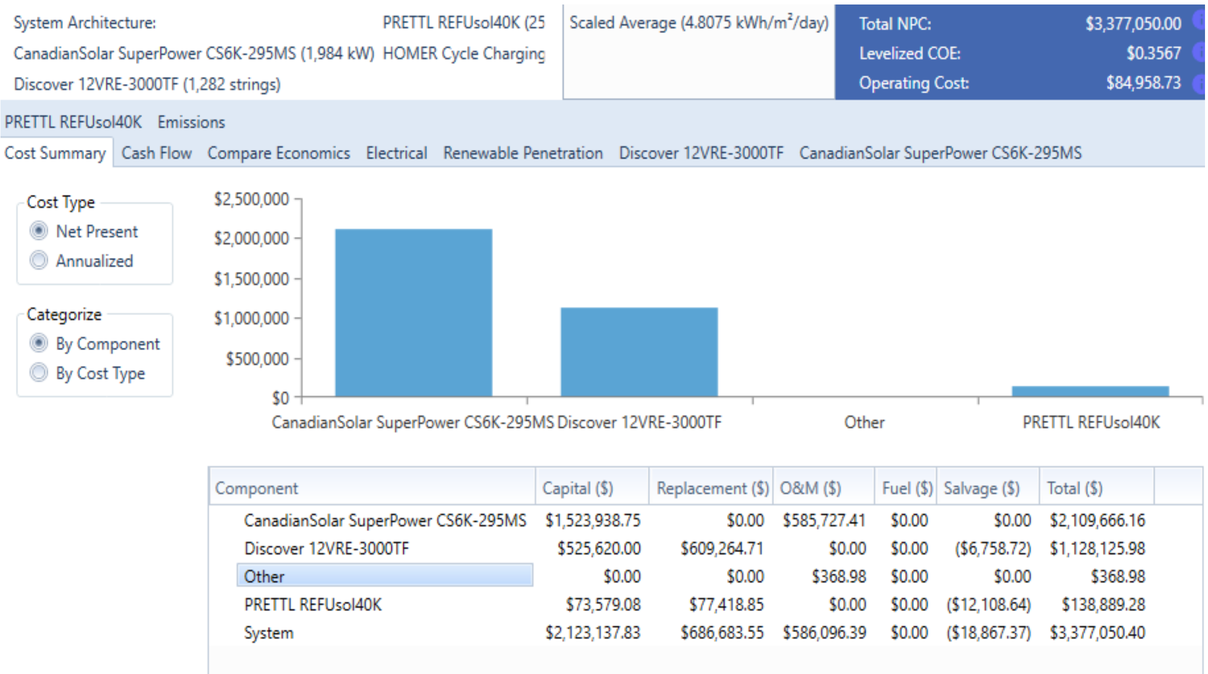
## 1. Ifite Anam Hourly Load Profile Load (KWh)

Yearly Load Data

Weekdays Weekends

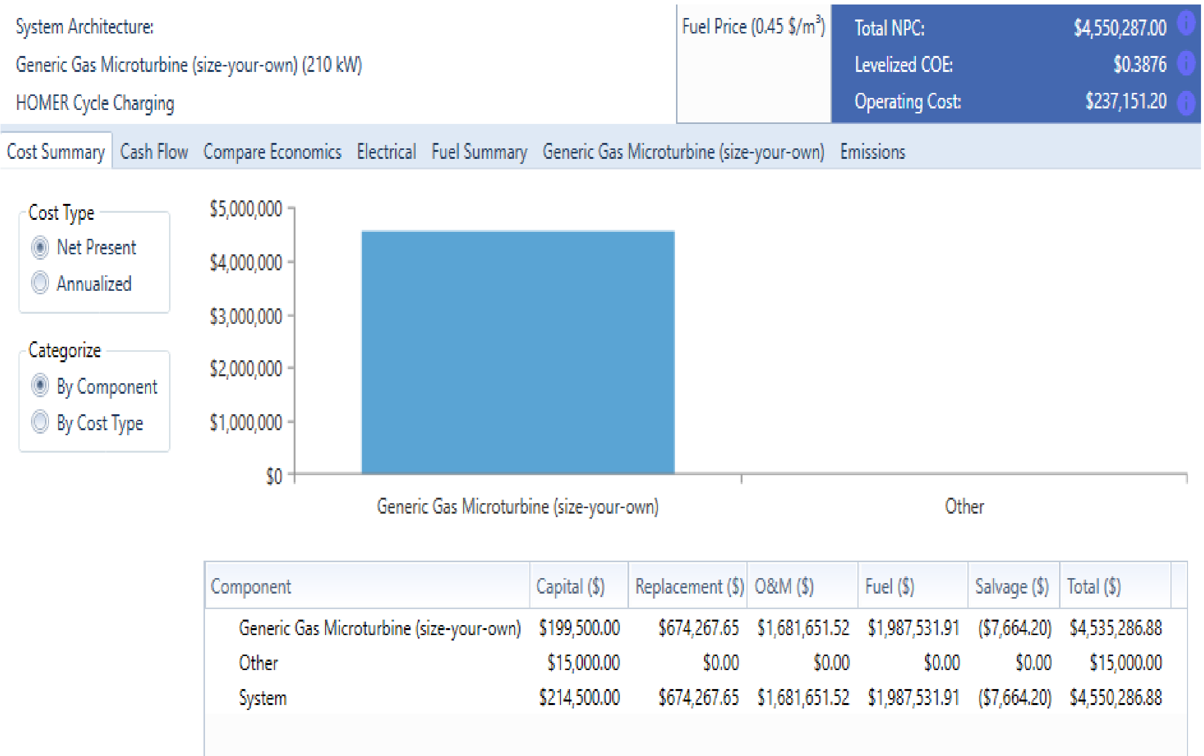
| Hour | January | February | March | April | May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 |
| 1 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 |
| 2 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 |
| 3 | 45.000 | 45.000 | 45.000 | 45.000 | 45.000 | 45.000 | 45.000 | 45.000 | 45.000 | 45.000 | 45.000 | 45.000 |
| 4 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 |
| 5 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 |
| 6 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 |
| 7 | 55.000 | 55.000 | 55.000 | 55.000 | 55.000 | 55.000 | 55.000 | 55.000 | 55.000 | 55.000 | 55.000 | 55.000 |
| 8 | 60.000 | 60.000 | 60.000 | 60.000 | 60.000 | 60.000 | 60.000 | 60.000 | 60.000 | 60.000 | 60.000 | 60.000 |
| 9 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 | 40.000 |
| 10 | 30.000 | 30.000 | 30.000 | 30.000 | 30.000 | 30.000 | 30.000 | 30.000 | 30.000 | 30.000 | 30.000 | 30.000 |
| 11 | 20.000 | 20.000 | 20.000 | 20.000 | 20.000 | 20.000 | 20.000 | 20.000 | 20.000 | 20.000 | 20.000 | 20.000 |
| 12 | 10.000 | 10.000 | 10.000 | 10.000 | 10.000 | 10.000 | 10.000 | 10.000 | 10.000 | 10.000 | 10.000 | 10.000 |
| 13 | 10.000 | 10.000 | 10.000 | 10.000 | 10.000 | 10.000 | 10.000 | 10.000 | 10.000 | 10.000 | 10.000 | 10.000 |
| 14 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 |
| 15 | 70.000 | 70.000 | 70.000 | 70.000 | 70.000 | 70.000 | 70.000 | 70.000 | 70.000 | 70.000 | 70.000 | 70.000 |
| 16 | 90.000 | 90.000 | 90.000 | 90.000 | 90.000 | 90.000 | 90.000 | 90.000 | 90.000 | 90.000 | 90.000 | 90.000 |
| 17 | 150.000 | 150.000 | 150.000 | 150.000 | 150.000 | 150.000 | 150.000 | 150.000 | 150.000 | 150.000 | 150.000 | 150.000 |
| 18 | 189.000 | 189.000 | 189.000 | 189.000 | 189.000 | 189.000 | 189.000 | 189.000 | 189.000 | 189.000 | 189.000 | 189.000 |
| 19 | 190.000 | 190.000 | 190.000 | 190.000 | 190.000 | 190.000 | 190.000 | 190.000 | 190.000 | 190.000 | 190.000 | 190.000 |
| 20 | 190.000 | 190.000 | 190.000 | 190.000 | 190.000 | 190.000 | 190.000 | 190.000 | 190.000 | 190.000 | 190.000 | 190.000 |
| 21 | 140.000 | 140.000 | 140.000 | 140.000 | 140.000 | 140.000 | 140.000 | 140.000 | 140.000 | 140.000 | 140.000 | 140.000 |
| 22 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| 23 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 |

## 2. Cost of electricity generation using Solar PV




| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| CanadianSolar SuperPower CS6K-295MS | $1,523,938.75 | $0.00 | $585,727.41 | $0.00 | $0.00 | $2,109,666.16 |
| Discover 12VRE-3000TF | $525,620.00 | $609,264.71 | $0.00 | $0.00 | ($6,758.72) | $1,128,125.98 |
| Other | $0.00 | $0.00 | $368.98 | $0.00 | $0.00 | $368.98 |
| PRETTL REFUsol40K | $73,579.08 | $77,418.85 | $0.00 | $0.00 | ($12,108.64) | $138,889.28 |
| System | $2,123,137.83 | $686,683.55 | $586,096.39 | $0.00 | ($18,867.37) | $3,377,050.40 |

## 3. Cost of electricity generation using Natrual gas micro turbine




| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| Generic Gas Microturbine (size-your-own) | $199,500.00 | $674,267.65 | $1,681,651.52 | $1,987,531.91 | ($7,664.20) | $4,535,286.88 |
| Other | $15,000.00 | $0.00 | $0.00 | $0.00 | $0.00 | $15,000.00 |
| System | $214,500.00 | $674,267.65 | $1,681,651.52 | $1,987,531.91 | ($7,664.20) | $4,550,286.88 |

## 4. Impact of emission charges on the cost of electricity generation in Iyiora Anam

Simulation Results

System Architecture:
Generic Gas Microturbine (size-your-own) (210 kW)
HOMER Load Following

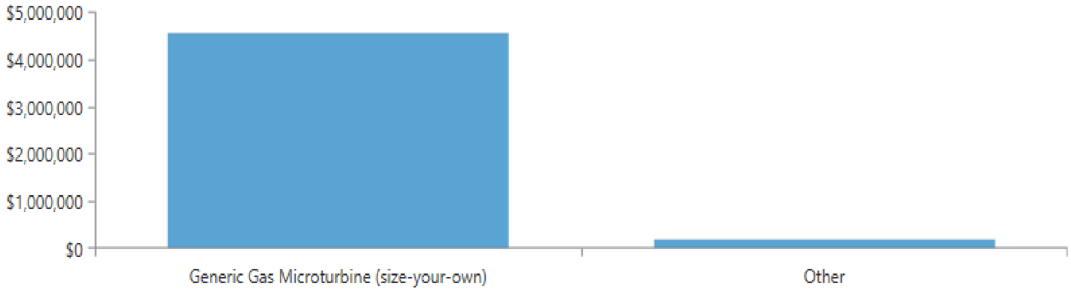
CO2 Penalty (20.26 )

Total NPC: $4,723,050.00
Levelized COE: $0.4024
Operating Cost: $246,600.70

Cost Summary | Cash Flow | Compare Economics | Electrical | Fuel Summary | Generic Gas Microturbine (size-your-own) | Emissions

Cost Type
- Net Present
- Annualized

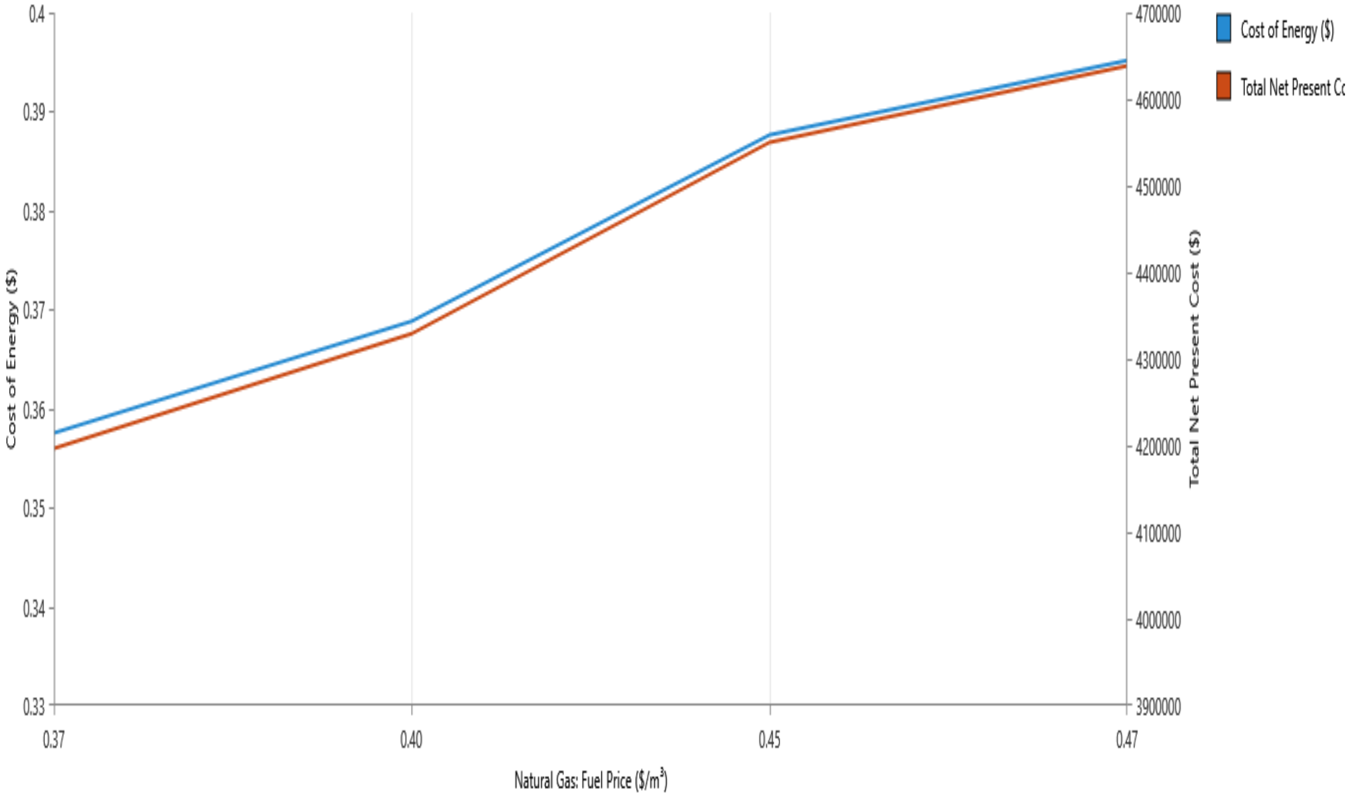
Categorize
- By Component
- By Cost Type




| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| Generic Gas Microturbine (size-your-own) | $199,500.00 | $674,267.65 | $1,681,651.52 | $1,987,531.91 | ($7,664.20) | $4,535,286.88 |
| Other | $15,000.00 | $0.00 | $172,763.07 | $0.00 | $0.00 | $187,763.07 |
| System | $214,500.00 | $674,267.65 | $1,854,414.58 | $1,987,531.91 | ($7,664.20) | $4,723,049.95 |

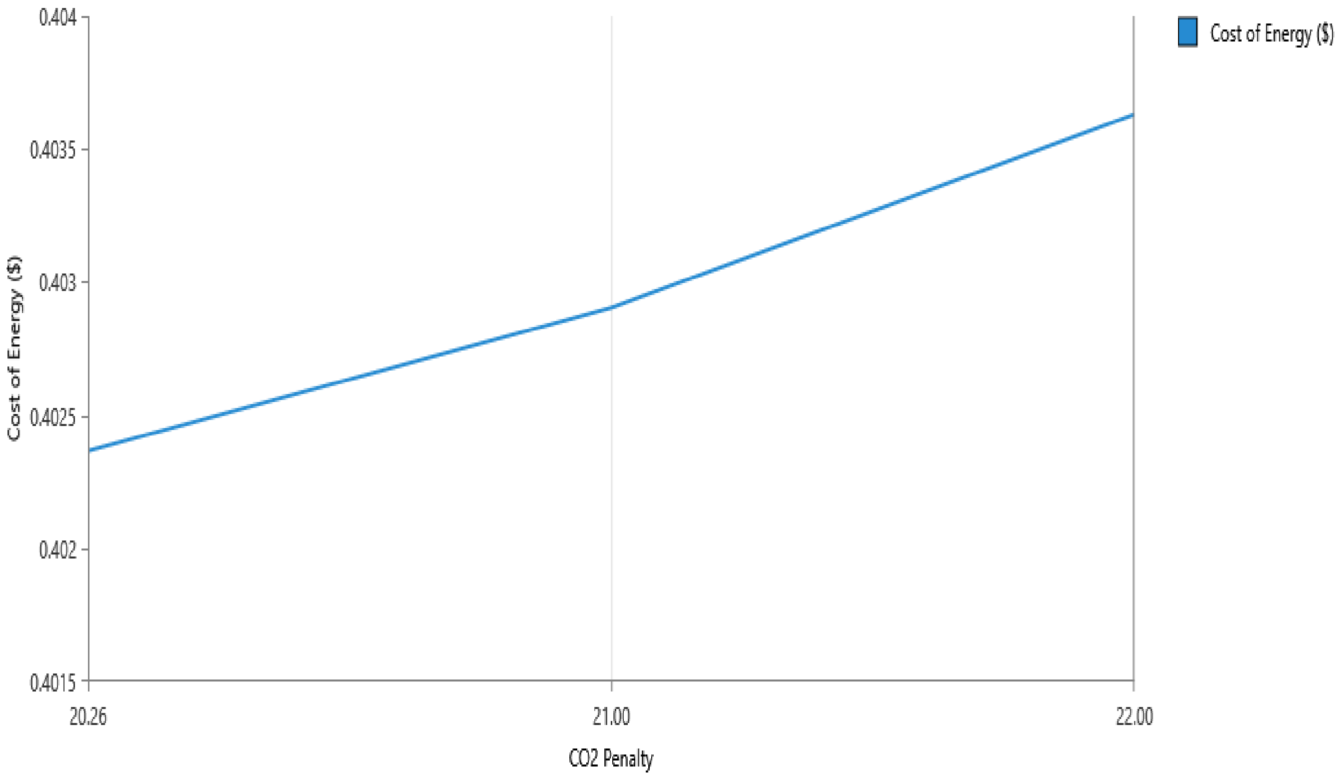
## 5. Sensitivity of cost of electricity generation using Natural gas powered turbine to changes in price of natural gas

| Sensitivity/Natural Gas Fuel Price ($/mÂ$^3$) | Architecture/Gas Gen | Architecture/Dispatch | Cost/COE ($) | Cost/NPC ($) | Cost/Operating cost ($/yr) | Cost/Initial capital ($) | System/Ren Frac (%) | System/Total Fuel (L/yr) | GasGen/Hours | GasGen/Production (kWh) | GasGen/Fuel (mÂ$^3$) | GasGen/O&M Cost ($/yr) | GasGen/Fuel Cost ($/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.37 | 210 | CC | 0.357546 | 4196948 | 217824.9 | 214500 | 0 | 241578.9 | 8760 | 650430 | 241578.9 | 91980 | 89384.2 |
| 0.4 | 210 | CC | 0.368834 | 4329450 | 225072.3 | 214500 | 0 | 241578.9 | 8760 | 650430 | 241578.9 | 91980 | 96631.56 |
| 0.45 | 210 | CC | 0.387648 | 4550287 | 237151.2 | 214500 | 0 | 241578.9 | 8760 | 650430 | 241578.9 | 91980 | 108710.5 |
| 0.47 | 210 | CC | 0.395173 | 4638622 | 241982.8 | 214500 | 0 | 241578.9 | 8760 | 650430 | 241578.9 | 91980 | 113542.1 |



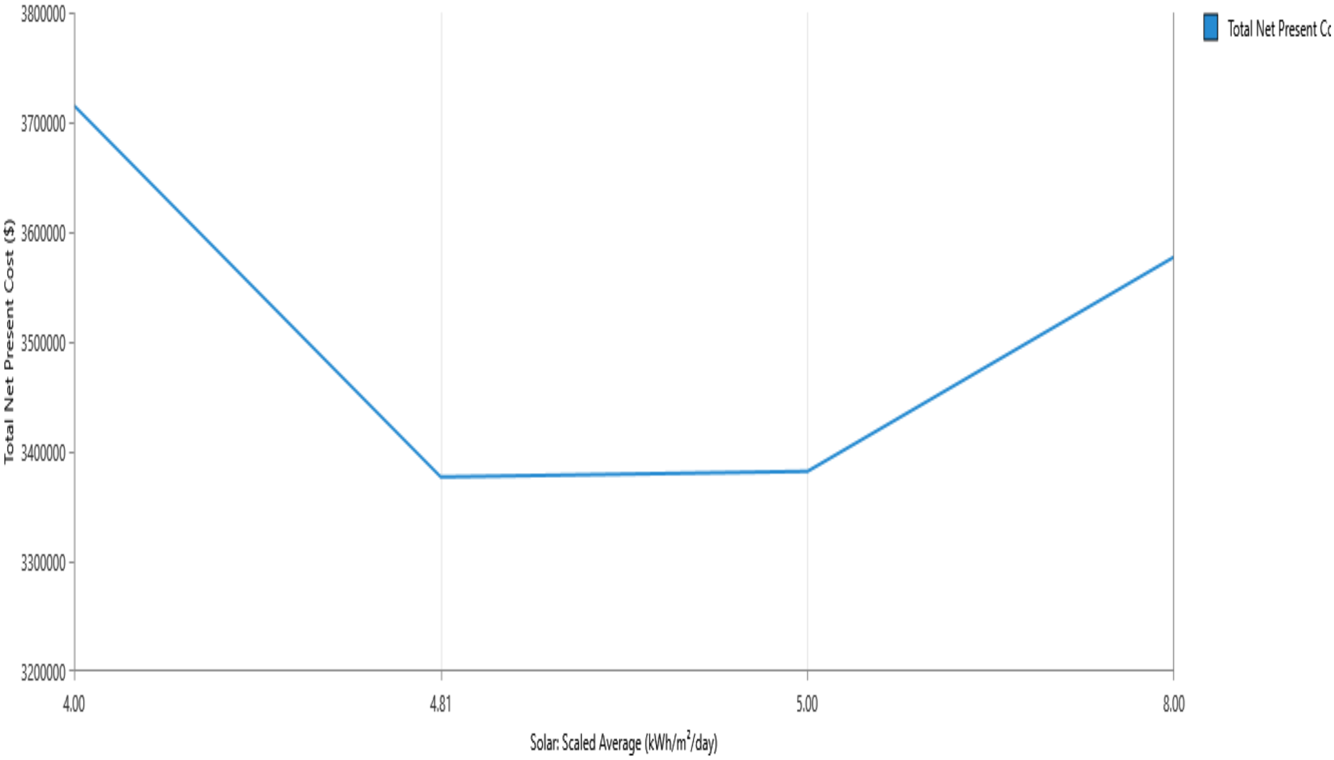
6. **Sensitivity of Cost of generating electricity using Natural gas plant to the variations of charges per ton of $CO_2$ emissions.**

| Sensitivity/CO2 Penalty | Architecture/Gas Gen | Architecture/Dispatch | Cost/COE ($) | Cost/NPC ($) | Cost/Operating cost ($/yr) | Cost/Initial capital ($) | System/Ren Frac (%) | System/Total Fuel (L/yr) | GasGen/ Hours | GasGen/ Production (kWh) | GasGen/ Fuel (mÂ³) | GasGen/O&M Cost ($/yr) | GasGen/ Fuel Cost ($/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20.26 | 210 | LF | 0.402366 | 4723050 | 246600.7 | 214500 | 0 | 241578.9 | 8760 | 650430 | 241578.9 | 91980 | 108710.5 |
| 21 | 210 | LF | 0.402904 | 4729360 | 246945.8 | 214500 | 0 | 241578.9 | 8760 | 650430 | 241578.9 | 91980 | 108710.5 |
| 22 | 210 | LF | 0.40363 | 4737888 | 247412.3 | 214500 | 0 | 241578.9 | 8760 | 650430 | 241578.9 | 91980 | 108710.5 |



## 7. Sensitivity of cost of electricity generation with Solar PV to changes in Annual Average Solar Irradiance

| Sensitivity/Solar Scaled Average (kWh/mÂ²/day) | Architecture/CS6K-295 (kW) | Architecture/Dis12V | Architecture/PRET40K (kW) | Architecture/Dispatch | Cost/COE ($) | Cost/NPC ($) | Cost/Operating cost ($/yr) | Cost/Initial capital ($) | System/Ren Frac (%) | System/Total Fuel (L/yr) | CS6K-295/Capital Cost ($) | CS6K-295/Production (kWh/yr) | Dis12V/Autonomy (hr) | Dis12V/Annual Throughput (kWh/yr) | Dis12V/Nominal Capacity (kWh) | Dis12V/Usable Nominal Capacity (kWh) | PRET40K/Rectifier Mean Output (kW) | PRET40K/Inverter Mean Output (kW) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.8075 | 1984.295 | 1282 | 255.4829 | CC | 0.356679 | 3377051 | 84958.73 | 2123138 | 100 | 0 | 1523939 | 3245306 | 43.58204 | 543817.9 | 3992.75 | 3194.2 | 0 | 73.23125 |
| 4 | 2282.657 | 1471 | 233.1544 | CC | 0.392427 | 3715240 | 87532.63 | 2423340 | 100 | 0 | 1753081 | 3576695 | 50.00716 | 540471.9 | 4581.385 | 3665.108 | 0 | 73.22591 |
| 5 | 1963.908 | 1289 | 300.9866 | CC | 0.357255 | 3382149 | 85282.66 | 2123456 | 100 | 0 | 1508281 | 3233195 | 43.82 | 544102.4 | 4014.552 | 3211.641 | 0 | 73.22354 |
| 8 | 2140.068 | 1646 | 195.0165 | CC | 0.377899 | 3577376 | 81494.16 | 2374597 | 100 | 0 | 1643572 | 3602587 | 55.95634 | 544232.6 | 5126.417 | 4101.134 | 0 | 73.21924 |



## 8. Research Grant Expenditure

| S/NO | ITEM | Approved PRICE (US$) | Actual PRICE (₦) | Actual PRICE (US$) |
|---|---|---|---|---|
| 1. | Homer Software and training sessions | 300 | 76,861.76 | 255 |
| 2. | Consultancy | 300 | - | - |
| 3. | Resource assessment from Solargis | 100 | - | - |
| 4. | Electricity Demand assessment | 500 | | 80 |
| a. | Local Assistance for data collection | - | 24,000 | 80 |
| 5. | Accommodation during data collection | 400 | | 480 |
| a. | Hotel accommodation | - | 84,000 | 280 |
| b. | Rent for internship @ Nibo (2 months) | - | 60,000 | 200 |
| 6. | Local travels for data collection | 600 | | 482 |
| a. | Car Hire | - | 120,000 | 400 |
| b. | Travel from Lagos to Awka | - | 13,000 | 44 |
| c. | Travel from Awka to Ibadan | - | 5,500 | 19 |
| d. | Travel from Ibadan to Awka | - | 5,500 | 19 |
| 7. | Local travel to Nigerian Electricity Regulatory Commission, Bank of Industry and Energy Commission of Nigeria. | 400 | | 390 |
| a. | Flight | - | 89,900 | 298 |
| b. | Taxi to Rural Electrification Agency (2 times) | - | 6000 | 20 |
| c. | Taxi from Rural Electrification Agency (2 times) | - | 6000 | 20 |
| d. | Taxi to the Airport (Arrival) | - | 3500 | 12 |
| e. | Taxi from the Airport (Arrival) | - | 4000 | 14 |
| f. | Taxi to the Airport (Departure) | - | 4000 | 14 |
| g. | Taxi from the Airport (Departure) | - | 3500 | 12 |
| 8. | Accommodation during travel (item 7) | 100 | 32,000 | 106 |
| 9. | Type setting, Binding and stationaries | 100 | | 103 |
| a. | Typing, Editing and printing | - | 25,000 | 83 |
| b. | Printing and Binding | - | DZD 2100 | 20 |
| 10. | Internet subscription | 170 | 58,600 | 195 |
| 11. | External Hard disk (1gb) | 50 | 30,000 | 100 |
| 12. | Internet modem | 30 | 9000 | 30 |
| 13. | Flight from Algiers to Tlemcen | - | DZD 84,285 | 795 |
| 14. | **Total** | **3000** | | **3000** |