Pan African University Institute of Water and Energy Sciences (including CLIMATE CHANGE)

# Master's Dissertation

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[Energy Engineering]

**Presented by:**

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# Feasibility Study for a Solar PV (Hybrid) Mini-grid System for Small Businesses in Lagos, Nigeria

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## Declaration

I Donald Chidera Abonyi, hereby declare that this thesis titled "Feasibility Study for a Solar PV (Hybrid) Mini-grid System for Small Businesses in Lagos, Nigeria" 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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## Dedication

To the African Union and the German Government; with love and my deepest gratitude!

## Acknowledgement

I am grateful to God for creating the Universe – maybe perhaps, He was the Big Bang or it was his making all along ☺. To my family; I am, because you are.

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***Donald Chidera Abonyi***
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**Abstract**

Small and medium-sized Enterprises (SMEs) have been recognized to be the cornerstone of every developing economy; for their contribution to national GDP growth and as a great employer of labor. In Nigeria: as at April 2019, the Nigeria Cooperate Affairs Commission (CAC) have in their records a total of 457,767 registered MSMEs. As at 2013, the National Bureau of Statistics reported that MSMEs in Nigeria employs 84.02% of the total labor forces in the country – making it the highest sub-sector annual GDP contributor with about 80.76% contribution to the growth rate. Regardless of the huge significance of SMEs to national development and GDP growth rate, small businesses are still facing numerous challenges; among which is poor electrification access. This has led most businesses – over 85% of businesses in Nigeria to rely completely on stand-alone generators for electricity generation. For a fact, reliance on gasoline generator and its attendant high cost of operation lead to the failure of many of these businesses and causes low return on investment for those with forbearance to survive among them. This research, investigated the techno-economic feasibility of solving the electricity challenge affecting small businesses in Sub-Saharan Africa using Nigeria as a case study location, with solar PV hybrid mini-grid system. A cluster market (plaza with estimated 200 shops) in the Computer Village District of Lagos, Nigeria was used as the SME case study for this research. Survey data was collected through in person and group interviews of the shop owners and the feedbacks used to inform on the consumption pattern and behavior of the shop owners. The education level, age and average weekly revenue data was also collected to help understand the end-user's ability to pay (ATP) and willingness to pay (WTP). The daily energy load demand data is then modelled using the HOMER Pro software to determine the feasible system for the case location. A Solar PV and Generator hybrid mini-grid system was found to be the most suitable for the shop owners with an initial Capital Cost (CAPEX) of ₦61.8M, total Net Present Value (NPC) of ₦245M ($674,705.50) and an effective Levelized Cost of Electricity (LCOE) of ₦21.73 ($0.06) per kilowatt hour. At an estimated daily peak consumption of 1055kWh/day, the shop owners will be saving an average of ₦150,000 ($413.09) monthly – resulting to an average increase in monthly profit of ₦750 ($2.07) for all of the shop owners by switching to this recommended system. The new system will also reduce $CO_2$ emission by 44% from the previous system in place in the plaza.

**Résumé**

Les petites et moyennes entreprises (PME) ont été reconnues comme la pierre angulaire de toute économie en développement, pour leur contribution à la croissance du PIB national et comme un grand employeur de main-d'œuvre. Au Nigéria : en avril 2019, la Commission nigériane des affaires de coopération (CAC) avait dans ses registres un total de 457 767 MPME enregistrées. En 2013, le Bureau national des statistiques a indiqué que les MPME au Nigéria employaient 84,02 % de la main-d'œuvre totale du pays, ce qui en fait le sous-secteur qui contribuait le plus au PIB annuel avec environ 80,76 % du taux de croissance. Indépendamment de l'importance considérable des PME pour le développement national et le taux de croissance du PIB, les petites entreprises sont toujours confrontées à de nombreux défis, parmi lesquels le faible accès à l'électricité. Cela a conduit la plupart des entreprises - plus de 85 % des entreprises au Nigéria - à compter entièrement sur des générateurs autonomes pour produire de l'électricité. En fait, la dépendance à l'égard des génératrices à essence et les coûts d'exploitation élevés qui en découlent entraînent la faillite d'un grand nombre de ces entreprises et entraînent un faible rendement du capital investi pour ceux qui ont l'abstention de la réglementation pour survivre parmi elles. Cette recherche a examiné la faisabilité technico-économique de résoudre le problème de l'électricité qui affecte les petites entreprises en Afrique subsaharienne en utilisant le Nigéria comme site d'étude de cas, avec un mini-réseau solaire PV hybride. Un marché en grappe (place avec environ 200 magasins) dans le Computer Village District de Lagos, au Nigéria, a été utilisé comme étude de cas des PME pour cette recherche. Les données de l'enquête ont été recueillies par le biais d'entretiens en personne et en groupe avec les propriétaires de magasins et des retours d'information utilisés pour informer sur les habitudes de consommation et le comportement des propriétaires de magasins. Les données sur le niveau de scolarité, l'âge et le revenu hebdomadaire moyen ont également été recueillies pour aider à comprendre la capacité de payer (ATP) et la volonté de payer (WTP) de l'utilisateur final. Les données relatives à la charge énergétique quotidienne sont ensuite modélisées à l'aide du logiciel HOMER Pro afin de déterminer le système réalisable pour l'emplacement du cas. Un mini-réseau hybride solaire photovoltaïque et générateur s'est avéré être le plus approprié pour les propriétaires de magasins avec un coût d'investissement initial (CAPEX) de ₦61.8M, une valeur actuelle nette totale (VAN) de ₦245M ($674,705.50) et un coût effectif nivelé de l'électricité (LCOE) de ₦21.73 ($0.06). Avec une consommation de pointe quotidienne estimée à 1055 kWh/jour, les propriétaires de magasins économiseront en moyenne ₦150,000 ($413.09) par mois - ce qui se traduira par une augmentation moyenne du bénéfice mensuel de ₦750 ($2.07) pour tous les propriétaires de magasins en passant à ce système recommandé. Le nouveau système réduira également les émissions de $CO_2$ de 44 % par rapport à l'ancien système en place sur la place.

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## List of Abbreviations

| | |
|---|---|
| MSME | Micro, Small and Medium-sized Enterprises |
| SME | Small and Medium-sized Enterprises |
| AFDB | African Development Bank |
| CBN | Central Bank of Nigeria |
| NASME | Nigerian Association of Small and Medium Enterprises |
| NERC | National Electrification Regulatory Commission |
| SMEDAN | Small Medium Enterprise Development Agency of Nigeria |
| REA | Rural Electrification Agency |
| FMPWH | Federal Ministry of Power, Works and Housing |
| NBS | National Bureau of Statistics |
| CAC | Cooperate Affairs Commission |
| IFC | International Finance Cooperation |
| SERC | Sokoto Energy Research Centre |
| IEEE | Institution of Electrical and Electronic Engineers |
| PWD | Public Works Department |
| GWEC | Global Energy Wind Council |
| FAO | Food and Agricultural Organization |
| NDPHC | Niger Delta Power Holding Company |
| TCN | Transmission Company of Nigeria |
| NDA | Nigeria Dam Authority |
| NEPA | Nigeria Electricity Power Authority |
| PHCN | Power Holding Company of Nigeria |
| IRENA | International Renewable Agency |
| UNDP | United Nations Development Programs |
| BOI | Bank of Industry |
| NESP | Nigeria Energy Support Program |
| GIZ | Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH |
| OPEX | Operation and Maintenance Cost |
| CAPEX | Initial Capital Cost |
| ESMAP | Energy Sector Management Assistance Program |
| SDGs | Sustainable Development Goals |
| OECD | Organization for Economic Cooperation and Development |
| IEA | International Energy Agency |
| UNDP | United Nations Development Programme |
| GENCOs | Generating Companies of Nigeria |
| USAID | the United States Agency for International Development |
| HOMER | Hybrid Optimization of Multiple Energy Resources |
| NASA | National Aeronautics and Space Administration |
| NAPTIN | National Power Training Institute of Nigeria |
| QGIS | Quantum Geographical Information System |
| DISCOs | Distribution Companies of Nigeria |
| kWh/kW | Kilowatt hour/Kilowatt |
| TWh | Terawatt hour |
| GWh | Gigawatt hour |
| MW | Megawatt |
| GDP | Growth Domestic Product |
| PPA | Power Purchasing Agreement |
| PV | Photovoltaic |
| $CO_2$ | Carbon dioxide |
| DC/AC | Direct Current/Alternating Current |
| LCOE | Levelized Cost of Energy |
| RESIP | Rural Electrification Strategy and Implementation Plan |
| NEPP | National Electric Power Policy |
| NPC | Net Present Cost |
| PSRP | Power Sector Recovery Plan |
| NREEP | Nigerian Renewal Energy and Energy Efficiency Policy |
| ESPRA | Electricity Power Sector Reform Act |
| FGN | Federal Government of Nigeria |
| NESG | Nigerian Economic Summit Group |
| RMI | Rocky Mountain Institute |

# Chapter One

## 1.0 Introduction

MSMEs is an acronym that stands for micro, small and medium scale enterprises. Micro, small and medium-sized enterprises are independent firms with no subsidiary and also employs a small number of employees. Different countries and continents have their unique criteria for classifying MSMEs. The European Commission defines SMEs as businesses that have less than 250 persons employed. Such businesses should also have an annual turnover rate of up to EUR 50 million, or a balance sheet total, but not more than EUR 43 million (European Union, 2015). Though SMEs play a vital role in global and national economic growth and development, it has no generally accepted definition. The interpretation of the range and the definition of what business constitutes a small and medium enterprise is unique to countries and institutions (Samuel Emezie, 2017). Notable institutions such as the World Bank, African Development Bank (AFDB), and the European Union (EU), define SMEs on the basis of size of business, capital assets, working capital, number of employees and turnover. Among these institutions' definitions, the most widely used is the European Union definition (Gibson, T., van der Vart, H. J, 2008). The EU defines SMEs in terms of employee size, turnover and/or total balance sheet as quoted in the first paragraph. In Nigeria, an SME is defined by the Central Bank of Nigeria (CBN), The Federal Ministry of Industry and Nigerian Association of Small and Medium Enterprises (NASME) as a business with turnover of less than 100 Million Naira per annum and/or less than 300 employees (Banji Oyelaran-Oyeyinka, 2011).

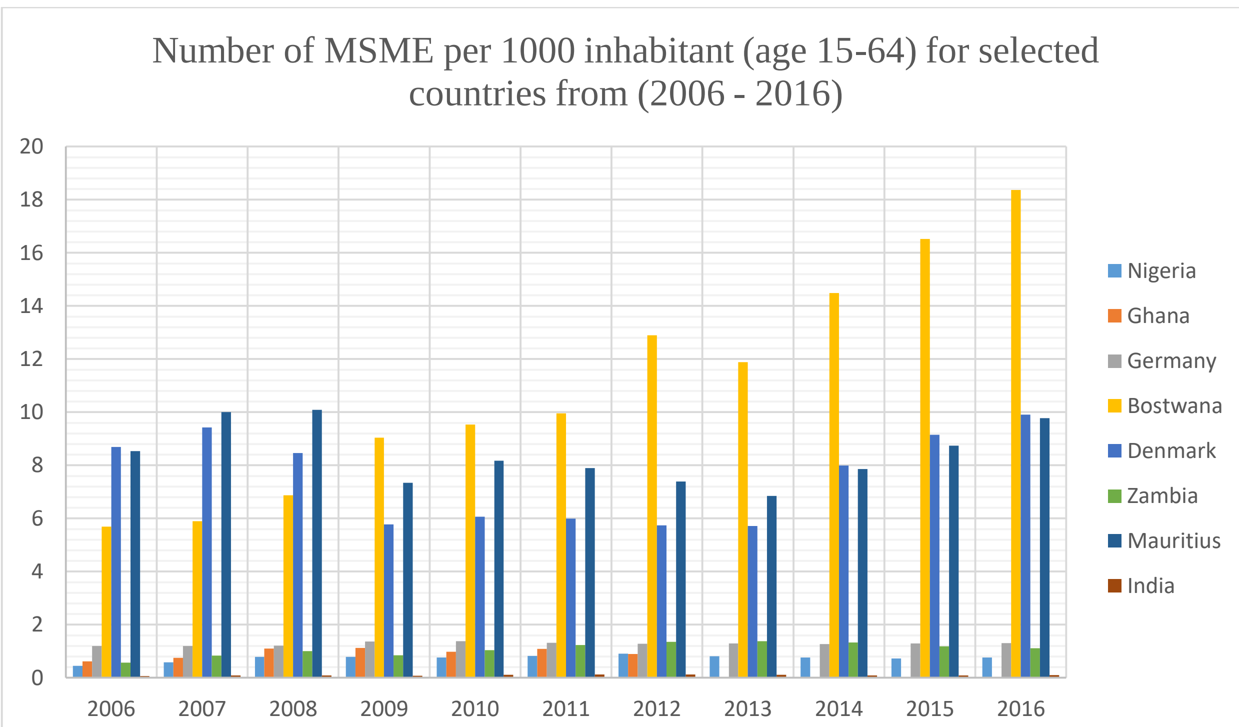
The Small and Medium Enterprise Agency of Nigeria (SMEDAN), addressed the issue of MSME definition through the National Policy on MSME in 2015 SMEDAN defines micro, small and medium enterprises in classifications – based on multiple criteria, such as number of employees and assets (excluding land and buildings) as listed below:

- "Micro Enterprises are those enterprises whose total assets (excluding land and buildings) are less than Five Million Naira with a workforce not exceeding nine employees".
- "Small Enterprises are those enterprises whose total assets (excluding land and building) are above Five Million Naira but not exceeding Fifty Million Naira with a total workforce of ten and above, but not exceeding forty-nine employees".
- "Medium Enterprises are those enterprises whose total assets (excluding land and building) are above Fifty Million Naira, but not exceeding Five Hundred Million Naira with a total workforce of between 50 and 199 employees".

In a case where the number of employees and assets criteria does not fit into any of the above categories, the employment-based classification will take precedence and the enterprise would be regarded as micro (NBS & SMEDAN, 2013).

(Fjose et.al, 2010) reported that up to 99 percent of all firms in developing countries are MSMEs. Also, (Scott et. Al, 2014) in their work on MSMEs insecurities in SSA, made similar conclusion as Fjose et.al (2010) by stating that around 90 million MSMEs provides over two third of the jobs in developing nations. As seen from the figure 1 below, the World Bank also reported that a substantial high number of MSMEs in Sub-Saharan Africa per inhabitant. This high number of MSMEs can largely be due to how MSMEs are defined in the different countries in the sub-Saharan region and also the population size of the countries. For example, from figure one, Botswana has the highest number of MSME per inhabitants, with India having the lowest. In some cases, especially in sub-Saharan African countries, there is no record of MSMEs because majority are considered as informal once they are not registered with the Cooperates Affairs Commission (CAC) of the various countries. Nigeria is one of the countries that record a huge number of informal business units which fall within the definition of an MSME. According to the 2013 report by the NBS and SMEDAN, Nigeria has an estimated 36,994,578 informal micro businesses with Lagos state making up the highest percentage with 8.72% of the total (NBS & SMEDAN, 2013). This research estimated that; about 30 percent of the currently registered micro, small and medium enterprises which based on the information given by the CAC in Nigeria to be 457,767 as at 24th May 2019 are still not registered and therefore considered informal businesses. This means that over 137,330 SMEs are considered informal because they are not yet registered with the CAC in Nigeria.

*Figure 1: Number of SMEs per inhabitant of selected countries 2010*



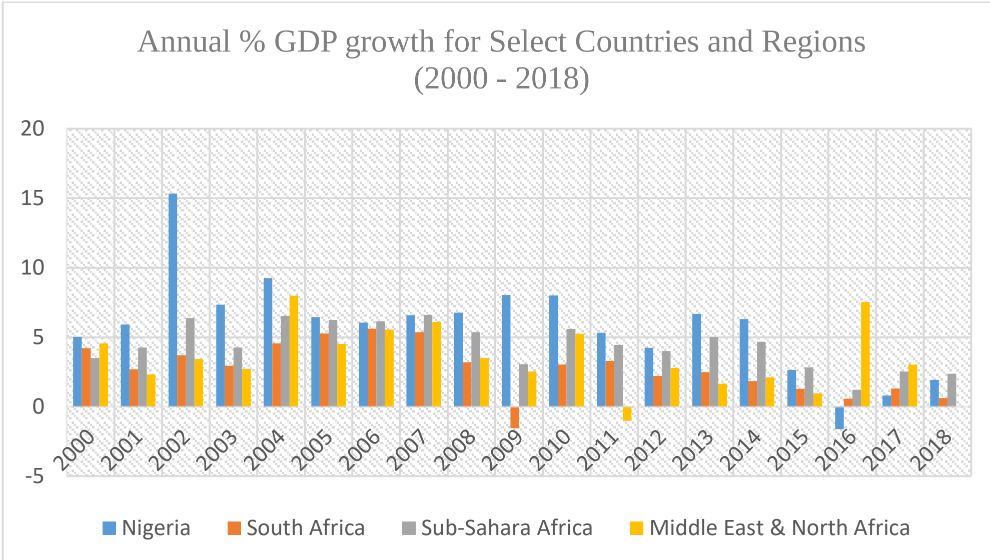

Source: World Bank's Entrepreneurship Survey and database 2019.

## 1.1 Importance of SMEs to Economic Development

A report by the Organization for Economic Co-Operation and Development (OECD) in 2004 stated that SMEs are vital to achieving decent and productive employment as they account for two-thirds of all jobs and also create the majority of new jobs globally. Same report also stated that in developing countries SME's account for 90 % of all firms outside the agricultural sector, drive employment as well as serve as a machinery for generating both local and foreign revenue (OECD, 2004). In Nigeria, studies reported by (IFC, 2006) shows that approximately 96% of Nigerian businesses are SMEs, compared to 53% and 65% percent in the US and Europe respectively. In the same report, it is also stated that approximately 90% of the manufacturing industries in Nigeria fall into the category of SMEs and they contribute an estimated total of 1% of annual GDP. In a 2013 joint survey report carried out by the National Bureau of Statistics (NBS) and the Small and Medium Enterprise |Development Agency of Nigeria (SMEDAN), a holistic view of the importance of the MSME to the Nigerian economy was outlined. The survey covered every key business sector in Nigeria ranging from the manufacturing sector, entertainment, to the Agricultural sector and covering over twelve business sectors. Based on the rebased GDP estimates of the Nigerian economy, its recorded that MSMEs in Nigeria contribute 48.47 percent, (N38.78 trillion), to Nigeria's national gross domestic product (GDP) as at the end of 2013. Other Services, which includes most activities not covered elsewhere in the classification and generally covered only by MSMEs, had the greatest contribution from the sub-sector GDP, with micro-enterprises contributing the bulk of about 80.76 percent. Also, MSME contribution to Nigerian export capacity stood at 7.27% as at 2013 (NBS & SMEDAN, 2013). The 2018 GDP average growth rate for Nigeria was at 1.9%, with a nominal GDP of 397.290 billion dollars for 2018 – making Nigeria one of the best performing countries in Sub-Saharan Africa, with South Sudan as the least performing with a negative GDP growth rate of about -11%. Also Sub-Saharan Africa was the only region that its member countries were recording a negative growth rate (South Africa in 2006, Nigeria in 2016) and an average growth rate which is less than that of Middle-East and North Africa. See figure 2 for more details. The single major reason for the poor economic performance is not only due to insecurity challenges but majorly due to poor energy access rate and crippled infrastructure that can support businesses in the countries.

The 2013 survey report by NBS and SMEDAN stated that as at 2013, Nigeria's total number of MSMEs stood at 37,067,416 (Micro-36,994,578, Small-68,168, and Medium-4670). The report also stated that Lagos state has the highest number of small and medium enterprises (11,663) as at 2013. Lagos state also has the highest number of micro enterprises (3,224,324), followed by Oyo state (1,864,954), while Nasarawa state recorded the least (382,086) (NBS & SMEDAN, 2013). The current number of registered SMEs in Nigeria according to the CAC is over 5 times the number of registered SMEs in 2013. This report, therefore estimate that in 2018, SMEs contributed about 79 billion dollars to the nominal GDP of Nigeria. The above statistics means that, as at 2013, the SMEs in Nigeria was already contributing close to 10% of the total GDP of the country, with micro businesses contributing over 70% to the GDP of the country. Since the most recent report from the NBS and SMEDAN is not yet made public, based on the seen trend; it is therefore safe to estimate that the percentage contribution of the SMEs to the economy of Nigeria has since increased and could be around 15 – 20%. This estimation is based on the increase in the number of registered small and medium businesses from the data obtained from the CAC as at May, 2019.

*Figure 2: GDP growth (annual %) 2000 – 2018*



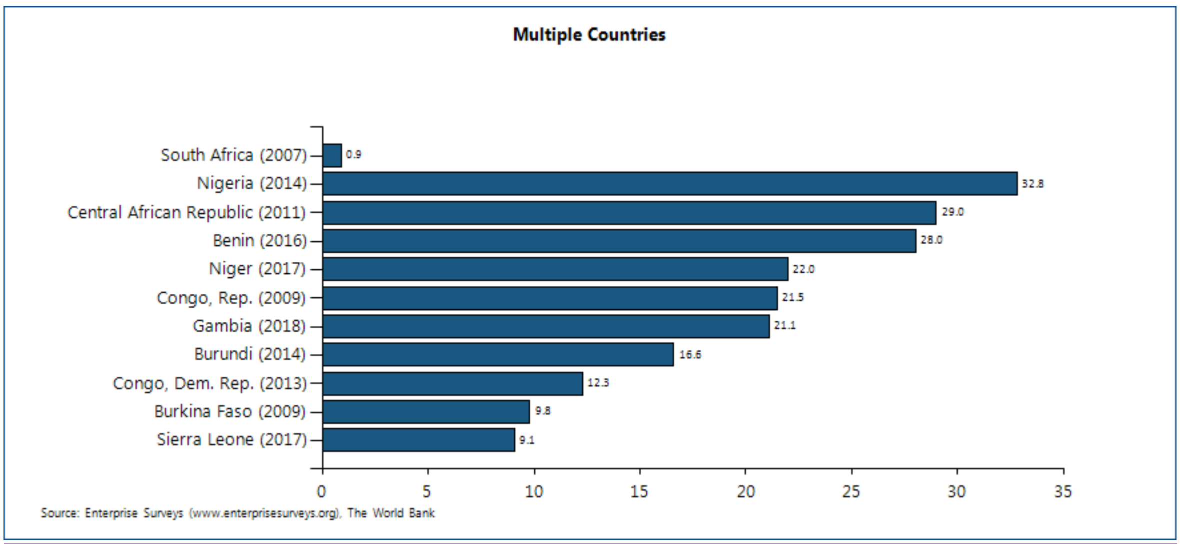

**Source**: World Bank national accounts data, and OECD National Accounts data files.

Based on the reports and conclusions from various research, we can state that SMEs constitute the foundation for development and economic growth in any given country or region; this conclusion is based on their contribution to national GDP and also to employment rate. NBS reported that the total number of persons employed by the MSME sector as at December, 2013 stood at 59,741,211 – representing 84.02% of the total labor force. In 2013, 43.32% of the owners of micro businesses were female, while 22.75% in small and medium enterprises. This shows that MSMEs plays a vital role in the Nigerian economy and deserves to be given the maximum possible attention towards providing a favorable environment to ensure that they can thrive.

According to (Charles Yeboah Frimpong, 2013), in his article, he stated that: "SMEs are the engine of social and economic development in Africa". (Samuel Emezie, 2017) in his thesis research, titled: Prospects and Challenges of SMEs in 21st Century Africa, reported that SMEs in Ghana are estimate to make up 70% of Ghana's GDP and 92% of its businesses. He concluded that SMEs are not only the engine of the economy, but can also serve as a stimulus for economic diversification in other sectors of the economy. His final recommendations include that SMEs with innovative technology; including cost effective and constant energy access have the potential to internationalize and enter foreign markets both regionally and globally.

At this point, this research has been able to establish based on the works done by numerous researchers the vital role SMEs including micro businesses plays in the world and in particular; the Nigerian economy, yet the SME ecosystem is still faced with numerous challenges in Nigeria. The (World Bank enterprise survey, 2010), stated that the most prominent challenge faced by SMEs in Nigeria is the lack of access to electricity. A more recent Enterprise Surveys as reported by (Scott et.al, 2014), shows that the proportion of firms reporting electricity as a major constraint varies between regions. The study reported 45% of firms highlighting electricity access challenges as a constraint in Sub-Saharan Africa (SSA) this was second to the Middle East and North African Region which has about 49%. In the same Enterprise survey by the Word Bank, by country; Nigeria came on top of the list of countries with a large proportion of SMEs owning or using generators to run their business due to no other alternative energy sources – with a percentage rate of 85% of SMEs and also the highest power outage per month (see figure 3). According to (GIZ, Mar 2015), an average duration of power outage for businesses is 7.8 hours in Nigeria, adding up to almost 256 hours of power outages per month (~34% of total hours) per month, this reality, further confirms the report by (Scott et al, 2014). Also, from the field data collected for this study, it shows that a hundred percent of business owners, has a backup energy source like generator in Nigeria. Only one business owner use battery plus standalone generator as his backup energy, the rest uses only standalone generator. Electricity access remains one of the greatest challenge to business growth and profitability in emerging economies like Nigeria.

*Figure 3: Number of Electrical Outage in a Typical Month by Countries*



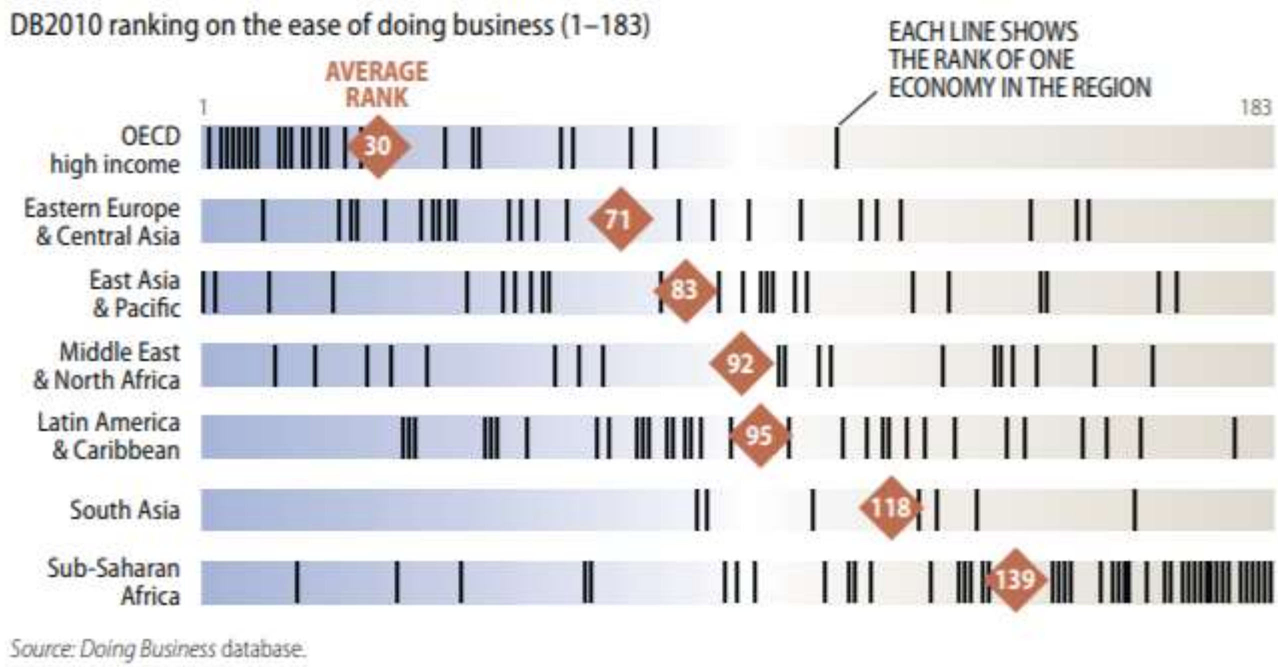

Source: World Bank Enterprise Survey, 2018

## 1.2 Barriers to SME growth in Sub-Saharan Africa

The main challenges confronting the operations of MSMEs in Nigeria as revealed by the (NBS, 2013) survey are access to finance and poor infrastructure (which on top of the list is access to electricity). According to the doing business report (Doing Business Survey: 2010, 2019), Sub-Saharan Africa on an average is ranked as the region in the world where it is most difficult to do business; scoring an average score of 139 in 2010 (see figure 4) and an even less impressive average ranking in 2019. The poor average ranking of the region is due to majority of the countries in the region which includes Nigeria (ranked at 146 in 2019) scoring very low on the ranking even though the government has been deliberate in ensuring policy improvements that supports businesses (largely MSMEs). Regardless, there are still a few countries in the region with a relatively healthy business environment. For instance, Mauritius is ranked as number 17 in 2010 but dropped to 20 in 2019, well above the OECD-average and South Africa was ranked as number 34 in 2010 but dropped significantly to 82 in the 2019 ranking. Rwanda did impressively well better than countries such as Spain, France and the Netherlands – ranking 29 in the 2019 report. See *Appendix 1* for more details on the doing business ranking of 2019. These ranking for the least shows that a lot needs to be done and also that the African continent especially the Sub-Saharan region can still grow and thrive into a strong and viable economy.

The reality on ground is that a lot of business are stills suffering and struggling with increasing challenges of poor infrastructure and difficulty in securing financing – hence the ranking. This work is focused in understanding the challenges that poor access to electricity causes MSMEs growth in Nigeria; using Lagos state as a case location.

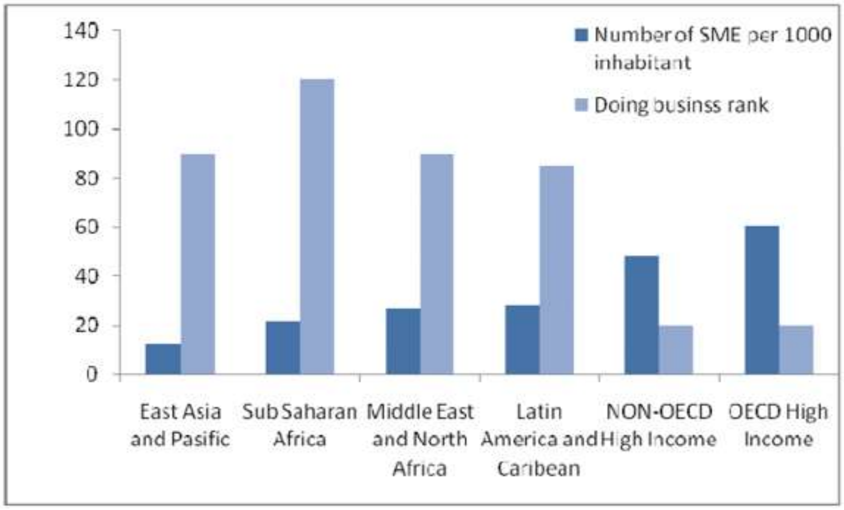
*Figure 4: Doing Business Ranking 2010*




Source: Doing Business Database, 2010

More research, suggest a close correlation between the doing business rank and number of SMEs per inhabitant in various countries. This assertion was reported by (Fjose et.al, 2010). The report published by (IFC, 2006) was used to confirm this correlation as seen in figure 5 below.

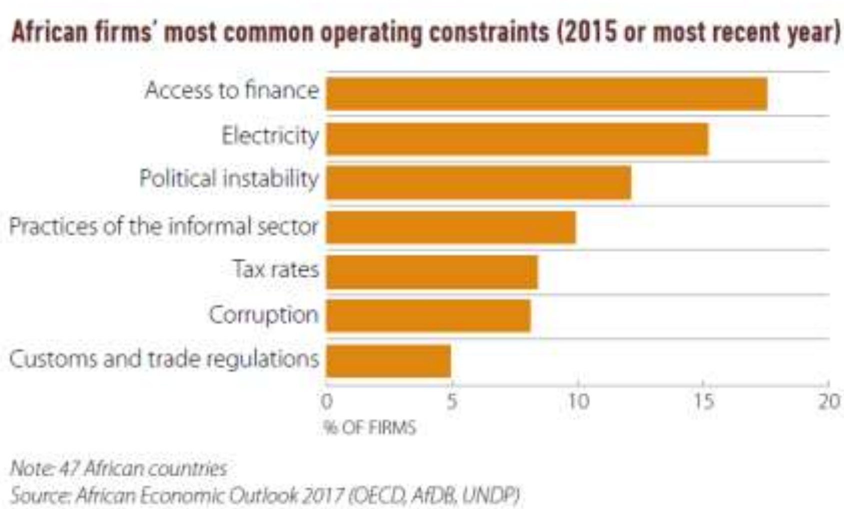
*Figure 5: Doing Business rank and Number of SME per Inhabitant*




Source: IFC 2006, Fjose et.al 2010

Electricity and access to finance is seen to have the most significant hindrance on businesses in Sub-Saharan Africa as at 2010 and has continued and even reported for the worse more recently in recent World bank surveys and the African Development Bank (AFDB) 2017 investment report (see figure 3 and 6). (Fjose et.al 2010, AFDB, 2017, World Bank Enterprise Survey 2018) all have stated that Africa is the only region where electricity is considered the most important hindrance to businesses especially to MSMEs. A survey collected from 47 African countries in a 2017 investment report by (AFDB &UNDP, 2017) reported on the factors that leads to constrains on investment in Africa and consequently affecting both large and small businesses. Among those factors were access to finances and Electricity with over 15% of the firms reporting (as shown in figure 6 below) that access to a reliable and affordable electricity is one the major challenges they are facing as a business.

*Figure 6: Most common operating constraints for SMEs in selected African countries*




Source: African Economic Outlook, (OECD, AFDB, UNDP)

(OECD & IEA, 2014) report, estimates that for the continent of Africa, the investments required, in other to achieve universal access to electricity by 2030 are at 19 billion USD annually (IEA 2011, World Development Indicators 2014). This is a lot of investment and can only be achieved if the African continent gives energy and access to finance for small businesses maximum attention. A similar report by the (IEA, 2017) stated that globally an estimate 1.2 billion people have no access to electricity and the majority percentage (over 90%) of these demography is resident in sub-Saharan Africa. The report went ahead to recommend that the most cost effective to fight global energy access rate towards the actualization of SDG7 is through micro-financed mini-grid and off-grid electrification. Just a few years back, the development of mini-grids was hindered by factors such as: gaps in policies and regulations, a lack of long-term sustainable financing, and a lack of capacity or interest among energy developers. The dynamics has changed now with now innovations and cost reductions in solar cells; making mini-grids an attractive option, hence the IEA, 2017 recommendation.

This research work aims to focus on the electricity challenges of micro, small and medium businesses in Sub-Saharan Africa (with Lagos, Nigeria as the study case location) and propose viable alternative energy solutions with a sustainable implementation strategy. The next section will expand more on the resulting consequence of poor energy access to the entire economy and especially on MSMEs.

### 1.3 Access to Electricity: An Obstacle to SME growth

As seen in Figure 6, access to electricity tops the list of the challenges for businesses in SSA after access to finance; with about 15% the firms from 47 African countries reporting it as a hindrance to their business. From Table 1, it can also be seen that more than 50 percent of businesses in Sub-Saharan Africa identify electricity as their major constraint in 2008. The statistics dropped to about 25 percent in 2010 but more recent survey report state that the percentage is at 45 percent (Fjose et.al, 2010) & (Scott et. Al, 2014). It is also a verifiable fact that the issue of poor electricity access rate is related to the generation capacity and the transmission infrastructure of every particular country and region. For example, in Nigeria at the moment, the total generation capacity of Nigeria is at about 12,500MW but just a little over 4,500MW is currently being transmitted through the national grid (USAID, 2018). It is also important to note that there has been a significant push for off-grid electrification and mini-grid development by the government. These efforts have led to an addition of close to 452KW to the generation capacity of the country but this generation is mostly completely off-grid (NESG & RMI, 2018).

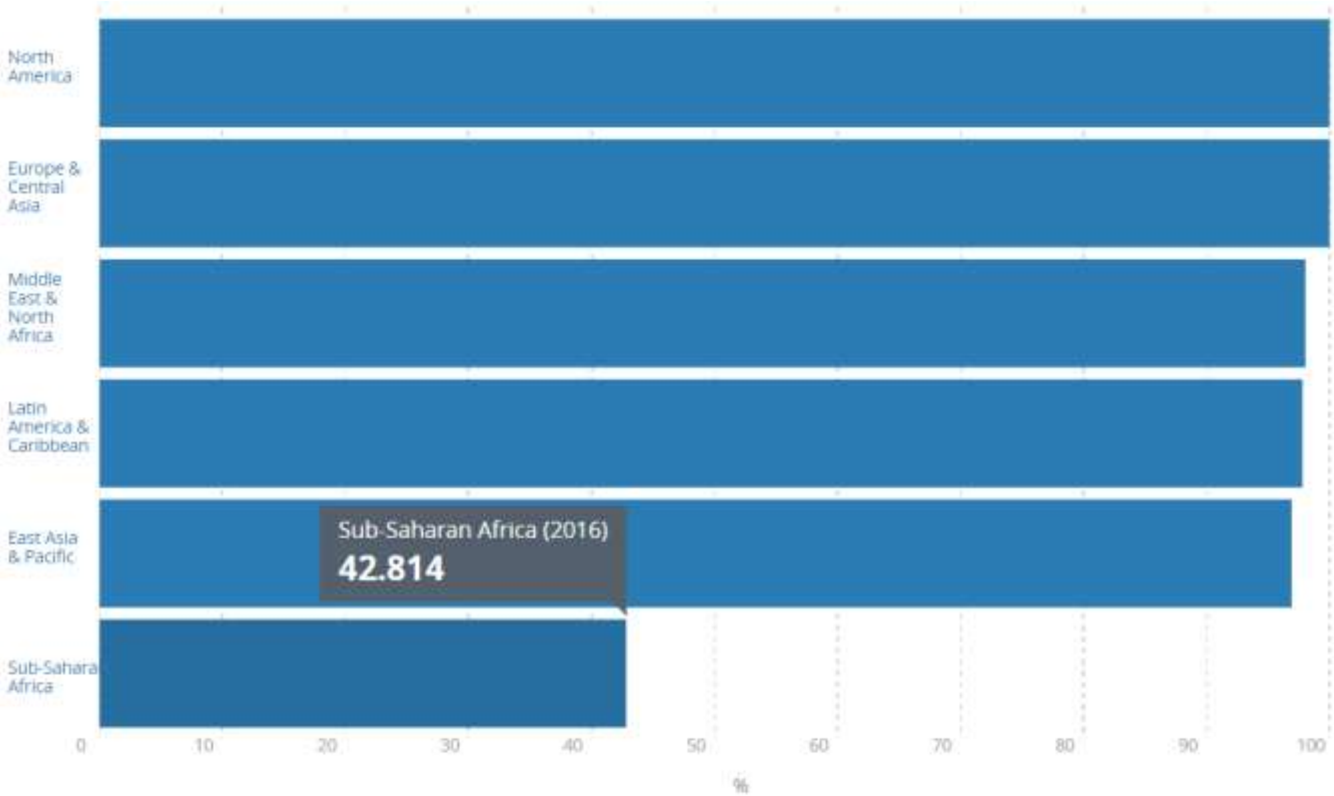
*Table 1: Electricity Obstacles Depending on Firm Size in Sub-Saharan Africa (2008)*

| | Small | Medium | Large |
|---|---|---|---|
| % of firms identifying access to defining electricity as their major constraint | 50 | 51 | 57 |
| Loss due to power outage | 6 | 5.6 | 5.5 |
| Average time of power outage per month | 68.1 | 73.4 | 64.8 |

Source: World Bank Enterprise Survey 2008, Fajose et.al 2010

Despite the increasing population of the region and the fact that the SSA region is the fastest growing region in terms of population in the world – with an increasing energy usage demand which has completely overwhelmed existing transmission lines and have led to even more increase in the cost of available electricity. Much attention is still not given by the leadership of the region towards national grid expansion and improved transmission infrastructure. Figure 7 shows that the current electricity access rate for the Sub-Saharan region (% of population) as at 2019 is at 42.814 percent while some other regions like the OECD areas have a 100 percent electricity access rate. Clearly the Sub-Saharan region is the lowest performing region towards the actualization of SDG 7 by 2030. Just earlier this year (2019), Ghana reanalyzed their plans to the actualization of a 100 percent electricity access for its population; at a current electricity access rate of 84.6%, Ghana has rebased it strategic framework and has move their target year to achieving 100 percent from 2020 to 2025 (SE4All Ghana, 2015). The progress of countries like Ghana is commendable but more work has to be done especially in larger economies like Nigeria. A Living Standards Measurement Study (LSMS) by the (World Bank & NBS, 2015), reported that over 80 million Nigerians lack access to a grid connected electricity, resulting to an electrification rate of 58% nationally and only 41% in rural areas. (ESMAP mini-grid Nigeria, 2107) during an event on the state of mini-grid investment in Nigeia, stated that for “the FGN vision 2020, towards achieving universal access to electricity by 2030, Nigeria would need to connect more than 1 million households per year and add roughly 25 GW to its power generation capacity”. A more recent study by Power for All – a global NGO which is focus on energy access in developing countries – estimated Nigeria’s energy access rate as at 2019 at 57.7% and an even worse access rate in the rural communities at 39% of the entire access rate of the country – affecting majority poor income earners and MSMEs (Power for All, 2019).

*Figure 7: Access to electricity (% of population)*




**Source**: World Bank, Sustainable Energy for All (SE4ALL) database from the SE4ALL Global Tracking Framework led jointly by the World Bank, International Energy Agency, and the Energy Sector Management Assistance Program.

Fjose et.al (2010) reported that "Prices of electricity in Sub-Saharan Africa (SSA) are the same, if not more than the prices in the OECD area. This means that electricity in SSA is almost twice as costly as in Latin America and Eastern and Central Asia". In addition to high prices of electricity, outage represents a serious problem for businesses in Sub-Saharan Africa. (Yepes et al, 2008) showed in their work titled: Making Sense of Sub-Saharan Africa's Infrastructure Endowment - A Benchmarking Approach: that with frequent power outage period, economic growth is slowed down. They estimate that annual GDP growth would have been 1-2 percentage points higher if access to electricity had been more stable – this implies that for a country like Nigeria, according to Yepes et.al (2008), with a 2018 GDP growth rate of 1.9, dropping from 2.1 from the previous year, a more stable electricity access would have led to a current Nigeria GDP growth rate of about 2.9 – 3.9 from 1.9. Government policies until recently (with the rise of interest to alternative and off-grid electrification), has led to a critical lack of investment in energy production. The situation in the investment on transmission lines in Nigeria is even worse; but some progress and efforts by the government shows that there is hope for a better energy landscape in Nigeria – with projects such as the Nigeria Energy Support Program (NESP) in partnership with the European Union and the German government. Such future is what this work is working towards becoming a part of (REA, 2019). It will not only be favorable for SMEs but for the entire economy of the country. Fjose et.al (2010) concluded in their work that "In order to improve access to electricity, large investments have to be made in electricity production and transmission. Better regulation and public purchase agreements must be put in place in order to boost investment".

The NESP project is currently investigating the best possible electrification planning strategy for the entire energy landscape of Nigeria in the second phase of the NESP project. One of the goals of the second phase is to map the entire geography of Nigeria and identifying the transmission lines in other to clearly understand its reach to the settlements in Nigeria so to know the best possible location that could require grid extension or the installation of a mini-grid. Clearly, the opportunities for mini-grid development is huge in Nigeria. This report will highlight some of the progress that has been made, the opportunities and the need for constant case location investigations and studies. This work also considered the implementation aspect of the solution.

One of the major setbacks of the efforts by the Federal Government of Nigeria (FGN) towards improving energy access rate as reported by USAID in their report in 2018 is that FGN has focused more on generation with little or no attention to the state of the transmission lines which are too weak and over labored, thereby resulting in multiple losses of energy in the transmission lines. The USAID stated in their report that even though Nigeria has the capacity to generate up to 12500MW of electricity, that currently, what is actually transmitted is around 4500MW through the national grid. This can be even less and has gone as low as 1MW in some seasons due to poor transmission lines (USAID, 2018). The news of the agreement between the Nigerian government and Siemens Gmbh of Germany to improve the transmission infrastructure of Nigeria to be able to transmit a capacity of 11000MW by the year 2023 is a welcomed development and if implemented, will greatly support businesses in Nigeria (CNBC Africa, accessed 26$^{th}$, August, 2019).

Considering the important role electricity plays in the running and the growth of SMEs in general, especially cold room businesses, and the fact that there are real alternatives energy sources. There is therefore a need to study into these challenges and establish a lasting solution that will take a holistic approach – looking at both the feasibility potentials and the implementation strategy of the alternative energy source. This study seeks to compliment the works that has been done by REA in Nigeria – to prove that there is a clean and cost-effective energy alternative toward ensuring the sustainability and profitability of MSMEs in Nigeria. The study will investigate the techno-economic possibilities of integrating solar PV hybrid system within the existing network at a tariff below the average 40 cent/KWh cost of electricity – which diesel generators currently cost small businesses in Nigeria as reported by the study conducted by the REA. The system will also be modeled to provide a capacity of 10KWh of electricity daily for each of the SMEs that will be considered (depending on the load demand) as a case study and the tariff modeled to decrease once the capital cost of the PV system has been recovered by twenty percent. The feasibility analysis will be focused on cluster market (Plaza) and will be considered four different implementation strategy, to determine the most economically and technically feasible alternative:

1. Solar PV/ Battery/ Diesel Generator as a backup
2. Solar PV/ Battery
3. Solar PV/ Diesel Generator
4. Diesel Generator/ Battery

The work also aims to develop a micro-financing model and a demand-side management approach (involving the end users in the development and maintenance strategy) that will be used in the implementation of the project once the feasibility has been established.

### 1.4 Existing Problems of PV Hybrid Mini-grid Systems in Nigeria

(NESG & RMI, 2018) reported in their mini-grid investment report on Nigeria that "Nigeria's large population and strong economy make it an attractive place to build the sector; the vast but underdeveloped mini-grid market offers revenue potential of ₦2.8 trillion (US$8 billion) annually". In this report, ten various operating mini-grid stations where reviewed and the opportunities and challenges for mini-grid development properly highlighted in the report. Some of the esisting challenges of mini-grid system development in Nigeria includes:

- Lack of community involvement in the system design and Poor load demand data capturing, leading to under or over sizing of mini-grid system
- Cost of equipment and the rampart availability of substandard solar panels, and batteries which results in low power output and poor system life's span.
- (NESG, 2018) reported that mini-grid costs are higher than the main grid but lower than small generators, which typically cost upward of ₦250 (US$0.70) per kilowatt-hour. It is also worth of note to state that the REA also stated in one of their reports that it is estimated to cost small businesses about USD40cent/kWh of electricity using standalone generators.
- Overlapping mandates and a lack of interrelations between the various MDAs due to lack of effective coordination and implementation of Nigeria's policy and institutional framework.
- Poor framework for the realization of value and the development of innovation in the electricity landscape in the country.
- Neglect by the Ministry of Finance towards aligning itself with the public and private sector actors to facilitate tax breaks and expedite customs processes incentives – these can be realized by eliminating VAT and tariffs on solar products. Implementing the zero percent Corporate Income Tax for off-grid operations of renewable energy companies, at least in the early years of operation until the capital cost of development is repaid, will greatly support investments.
- Poor grid infrastructure also is a huge challenge, making it nearly impossible for the implementation of the feed-in-tariff and the net-metering incentives for off-grid energy developers and customers.
- Available financial instruments to support mini-grid development, are still difficult for developers to access due to lack of a standardized financing template for developers.

## 1.5 Problem Statement

Numerous researchers including the agencies of the federal government of Nigeria and reports by the World Bank through the enterprise survey do confirm the fact that one of the most challenging hindrance to business growth and profitability is poor access to electricity. The case of access to funding for new and already existing businesses is important, but this work will be focusing on the issues of energy access for small businesses in Africa with a focus in Nigeria. Most Nigerian businesses have now turned to standalone generators which are increasing inefficient and expensive, just to keep up with business demands. The use of standalone generators has resulted to the cost of energy per kilowatt hour of about 40cents as reported by the REA – leading to loss of profit and the closure of most SMEs in Nigeria. For the state of Lagos alone, with an estimated 25,000 SMEs and over 75% of businesses running on standalone generators or sharing one. The issues of poor energy access, is clearly a huge challenge for businesses in Nigeria (especially MSMEs). It is therefore obvious why most businesses in Nigeria remains perpetually at the MSME level, with no room to scaling up due to little to now profitability in revenue – because most of the money generated goes most into energy access. It is to the benefit of the Nigeria economy that MSMEs are given the best possible ecosystem to thrive because of the important role they play to the economy.

## 1.6 Justification of Study

From the feedback gotten from field data collection, among the many problems faced by Micro, Small and Medium-sized Enterprises in Nigeria, the problem of poor energy access and power supply remains significant and affects majority of MSMEs in Nigeria. Over dependent on gasoline generator (which cost and environmental impact is constantly raising) leads to the failure of many businesses in Nigeria especially MSMEs. The EIA & IEA also reported in 2017 that one of the most cost effective strategy to achieve universal energy access by the year 2030 especially with the regards to Sub-Saharan Africa will be through micro-financed off-grid mini-grid electrification (IEA; EIA, 2017). This thesis research is therefore timely and very much justified. It aims to proffer an innovative and profitable solution through a thorough feasibility study; considering the end user's consumption behavior, ability to pay and an implementation strategy that considers the community and reflects a demand-side management approach. Our hope is that, once our recommendations are implemented, it will lead to providing a sustainable solution to the energy poverty challenges facing MSMEs in Nigeria, through the deployment of a cost effective Solar PV hybrid mini-grid system that will serve the business communities in Nigeria and by extension all over the continent.

## 1.7 Research Objectives

- To investigate the techno-economic possibilities of integrating solar PV mini-grid system within the existing network for SMEs in Lagos Nigeria at a rate less than 40 US cent/KWh

- To investigate the impact of the use of Solar PV hybrid system (mini-grid) on business profitability, employability and environmental impact

- To identify the most cost-effective system design (PV/Diesel/Battery – hybrid mini-grid system)

- To develop a financial model that is suitable for different business sectors based on their revenue stream and location, to ensure community capacity building and demand-side management implementation approach.

### 1.8 Limitations of Research

The proposed feasible system we have the following limitations:

1. The system is specifically for the selected case study location (Computer Village Business District Lagos, Nigeria) and might not be the optimal configuration for a different location, even with a similar business scenario due to the possibility of having different environmental and climatic conditions.
2. Due to poor availability of other renewable energy resource potential (like wind) and also primary energy source data in the case study location, only solar energy and data from NASA Satellite repository was used for this study
3. The study also does not consider the issues related to the mini-grid stability.
4. This study did not factor in corrective factor calculation for the case location in case of future load expansion.
5. The accuracy of HOMER simulation results is largely dependent on the quality of the input data. This limitation is significant given the fact that there is possibility of errors in the data collection process.

### 1.9 Key Assumptions

For accomplishment of the goal and objectives of this research, the following assumptions were made:

1. Rate of inflation for all types of costs has been considered same throughout the lifetime of the project.
2. NASA satellite-derived meteorology and solar data are sufficiently accurate for gauging PV systems
3. The annual variations of solar radiation occurring throughout the project lifetime remains the same
4. The design load required for the business district is within the medium range of mini-grid sizing and that the issues of system stability will be normalized by the inverter and considered to be insignificant
5. Seasonal variations of load demand were not considered in the load estimation
6. The Shop owners’ equipment to be operating at their rated power and at the standard factory efficiencies
7. A similar consumption pattern was assumed for all the shops in the plaza

## Chapter Two

### 2.0 Literature Review - Introduction

Climate change related challenges, rapid population growth, the ever-increasing energy demand and the United Nations call (through Sustainable Development Goal number seven – SDG7) for an inclusive energy access strategy have made access to alternative energy supplies imperative. This global energy trend applies to Nigeria, which according to the World Bank has a population of 186 million citizens and a continuously growing demand for energy. Our hope is that, through this research we contribute towards a sustainable solution to the energy challenges facing our continent and Nigeria in particular (World Bank Data, 2019).

This very chapter looks at the theory, concepts and the background research that has been carried out by various academics and researchers all over Africa and beyond with most of them coming to similar conclusion on the importance of energy access to economic growth and poverty alleviation. According to IEA, in their 2017 report an estimated 40% of the world's poor live in villages that are typically too remote to be feasibly reached via grid extension in the near term. Making mini-grid one of the only feasible solution towards ensuring that affordable energy get to these locations and especially to businesses in these locations. National Electric Power Policy (NEPP, 2001) policy report, it states that the FGN aims to make reliable electricity available to 75% of the population by 2020, and 90% by 2030, with a minimum of 10% share of the energy provided by renewable sources by 2025. A research done by (Yadoo & Cruickshank, 2012), concluded that renewable energy technologies contributes towards poverty alleviation and at the same time to the fight against climate change by supporting small businesses and enterprises in communities.

(Scott, A. et.al, 2014) reported that, the percentage of SMEs in developed nations citing electricity as a major constraint is half of the numbers in the Sub-Saharan African and the Asia regions. Their report also stated that the cost and time spent on acquiring electricity were much higher in developing countries and regions when compared to the developed regions. Scott et.al (2014) concluded that lack of reliable electricity supply to most SMEs in low income countries and its high tariffs to SMEs has become the highest challenge most SMEs encounter in developing countries. They recommended that Policy makers can help to mitigate the impact of electricity insecurity on SMEs by ensuring that outages are planned and by facilitating access to alternative supplies of electricity, including generators and renewable energy.

(Udochukwu B. Akuru & Ogbonnaya I. Okoro, 2014) published a work on the economic implications of constant power outages on SMEs in Nigeria, they concluded that: "apart from the internal devastating effect on SMEs, constant power outages have a major connection with the recent trends of big companies closing or relocating from Nigeria". Related research was conducted by (Ologundudu, Mojeed Muhammed, 2015) on his work titled: The Impact of Electricity Supply on Industrial and Economic Performance in Nigeria. He concluded that, for Nigeria to drive economic development through industrialization, the country should fix the electricity supply problem. Also, (Yakubu Zakariya Nurudeen et.al, 2018) on their work titled: An Investigation of Electricity Power Fluctuations and Performance of Small and Medium Enterprises in Dekina, Kogi State, Nigeria, showed the differences between SMEs that utilized installed capacity and those that does not consume installed capacity. These differences can be in terms of operation cost, productivity and competitive. They concluded that “SMEs that utilized installed capacity witness reduced operation cost, increased productivity, higher competitive edge, larger market share, a greater contribution to poverty and unemployment reduction”. Field research conducted by (Doe, F. and Asamoah, E.S, 2014) in Ghana titled: The Effect of Poor Electricity Supply on SMEs Growth in Ghana, concluded that, the lack of reliable electricity sources and the resulting high tariffs, have a significant negative impact on the quantity and quality of business production.

The EU report on SMEs as quoted in chapter one stated that SMEs are the engine of the European economy. They do this by driving job creation and economic growth and also ensuring social stability. The report recognized the contributions made by SMEs in 2013: creating 88.8 million jobs throughout the EU with just over 21 million SMEs. In a report published by (Andrew Scott et.al, 2014), they concluded that: “Renewable energy offers the potential of reliable alternative electricity for SMEs”. The Rural Electrification Agency of Nigeria (REA) in 2017 published their findings, saying that a significant amount of the Nigerian economy is powered largely by small-scale generators (10–15 GW) and almost 50% of the population have limited or no access to the grid (REA, 2017).

Stand-alone generators are mostly used to deliver power to SMEs in Nigeria; resulting to an increase in the cost of energy generation and as a result, causing lack of profit and low return on investment for most businesses – leading to business shutdowns and more unemployment in Nigeria. REA also established that the developing off-grid alternatives to complement the grid will create a $9.2B/year (₦3.2T/year) market opportunity for mini-grids and solar home systems that will save $4.4B/year (₦1.5T/year) for Nigerian homes and businesses (majority of the business being MSMEs). The same report concluded that the limited access to the grid has led to most Nigerians and their businesses spending almost $14 billion (₦ 5 trillion) annually on inefficient generation that is expensive to the tune of $0.40/kWh (₦140/kWh) or more (REA, 2017). Energy transition from conventional to more unconventional sources and or a blend of both seems and has been reported by the REA and EIA to be one of the major ways for the future towards achieving an inclusive, sustainable and affordable energy access especially in Africa. This transition, which (Udoka et.al, 2018) described as the “decarburization of the energy system”, is driven by factors such as economic, sustainable and social perspectives. In the case of Nigeria, the economic impact to the economy has been extensively reported by the REA. Also noteworthy are the noise and climate change impacts of fossil-fuels, national energy security and an increasing energy load demand due to increasing population growth rate. The REA also encouraged decentralized generation; such as mini-grid and off-grid electrification strategy especially for rural communities. More recently, in Nigeria the Blockchain technology and an energy user cooperative distribution strategy (open electricity market) are all under consideration as the way forward towards improved energy access rate in Nigeria, through energy transition (REA website, accessed 14$^{th}$ June, 2019).

Various statistics including that from IEA, AFDB and the World Bank shows that a large proportion of the African population are incapable to access current energy services like solar photovoltaic, grid-electricity and fuel-based production due to the mere fact that very few number of the population actually can pay for it because most are living below the poverty line according to the (World Bank Data, 2019; IEA, 2017; AFDB, 2018). EIA in their 2017 report, reported that "most of the African population depends on the biomass for cooking fuel and heat; on kerosene wick lamps, battery-operated flash lights, or candles for lighting; and on human or animal energy-based mechanical power for tilling and weeding land, grinding and crushing, agro-processing, or transport". The African Development Bank is one of the leading investment organizations in Africa and has given itself five priority areas – the High 5s. the primary aim of the High 5s is to transform Africa's prosperity through long-term investments – working on issues from energy, agriculture and industry. One of the High 5s which is very much connected to this research is the light up and power African goal 2025. The bank has made a lot of progress towards achieving this particular goals and this has resulted to improved energy access rate in various regions on the continent; translating to a business ecosystem that is profitable for MSMEs (AFDB, 2018).

## 2. 1 Mini-grid Hybrid System Case Studies of Selected Sites in Nigeria and Around the World

Hybrid power generation has been done in many countries in the last few decades to provide electricity that can power discrete communities and institutions. Determination of optimal design of the hybrid systems in terms of cost and reliability is of great importance to make sure that the system is not over sized or undersized. The NESP in their support for the development of mini-grid in Nigeria has recorded as at January, 2019 30 mini-grid system currently operated in Nigeria with one of them powered by Biomass energy source. The GIZ also reported based on NESP collected geo-referenced data on population clusters, load centers and settlement data, an estimated 8,000 potential sites that are suitable for mini grids and a projection market growth of up to 430 by 2023 (GIZ-NESP, 2019).

In July 2015, GVE Projects, Ltd., in collaboration with the Bank of Industry Nigeria (BOI), United Nations Development Program (UNDP) and the Institute of Electrical Electronics Engineers (IEEE), announced the completion of a 37.8 kW of PV solar-based mini-grid pilot project in Bisanti community of Niger State, Nigeria. The project currently serves 200 households (approx. 1,600 people, at 8 persons per house) and utilizes a pay-as-you-go platform. It is estimated to offset about 365.2 metric tons of $CO_2$ annually in the community. The project cost $250,000, with 90% of the financing coming from Bank of Industry Nigeria (equity and debt financing), and a 10% grant from IEEE. A lot of benefits has resulted in this community due to this project aside from the job creation of an estimate of over N2.7 million naira, to extended business operating hours, 50% reduction in energy-related expenditures and children use street lighting points to study and play at night (ESMAP mini-grid, Abuja 2017). GVE Projects, Ltd., in collaboration with the Bank of Industry Nigeria (BOI), United Nations Development Program (UNDP) and the Institute of Electrical Electronics Engineers (IEEE), also announced the implementation of a 40.95 KW of PV solar-based mini-grid pilot project in 2017 at the Kperegi/Swasun community in Niger state, Nigeria. Just like the Bisanti community project, this project will utilize a pay-as-you-go payment model but will go further and train local community members to oversee the daily operation of the site after commissioning. As at the time it was commissioned in November, 2017, it served 200 households – approximately 1,600 people at 8 persons per house – and is estimated to offset up to 365.2 metric tons of CO2 annually in the community. It also led to a 50% reduction in energy-related expenditures and an 80% reduction in malaria cases in the community (ESAMP mini-grid, Abuja 2017). The project cost was $250,000, with 68% of the financing coming from the Bank of Industry, and the rest 22% from UNDP (grant), 10% from GVE (equity contribution).

In 2011, NERC listed 58 solar-based rural electrification projects across the country. From a survey including 53 companies carried out by the Nigerian Energy Support Programme (NESP) in 2015, in total these companies had installed 115 MW of off-grid photovoltaic combining mini-grids and stand-alone systems as Independent Power Producers (IPP) under the bill which was passed under the leadership of the previous Minster of the FMPWH – which gives energy consumers with load demand up to 40MW and above the option to generate their energy if they are not satisfied by the DISCOs delivery. Most of them have been installed for residential or commercial purposes in un-electrified rural areas. Some have also been built in grid-connected areas as backup systems. In 2014, the FMP launched a new national program called “Operation Light-Up Rural Nigeria”. The project ended up installing three solar-powered mini-grids in each of the 36 federal states. In early 2014, the first pilot solar-driven system under the scheme was installed by a French company in Durumi, Bwari Area Council of Abuja, using a 3.5 kVA standalone system; three further systems have since been installed in Abuja. The Sokoto Energy Research Centre (SERC), together with the World Bank, the Energy Commission of Nigeria and the Sokoto Government, installed a hybrid mini-grid combining 10 kW solar and 2 kW wind power in Danjawa Village, Sokoto. A PV/wind hybrid plant with 10 kW of solar PV and three wind turbines with a combined capacity of 15 kW has also been installed at the NAPTIN Regional Training Centre in Kainji. This project was funded by the German Federal Foreign Office and implemented by GIZ in the first phase of the NESP project in Nigeria.

More cases of mini-grid development have been reported in literatures. For example, (Ranaweera, June 2013), carried out a study in his thesis research on the techno-economic optimum sizing of hybrid renewable energy systems for rural electrification in Sri Lanka. The paper presented hybrid systems that could supply electricity to a rural community in Sri Lanka. A rural village from the Siyambalanduwa region in the country containing approximately 150 households which results in the daily electricity demand of 270kwh with a night peak of 25kw was chosen as a target. His findings proved that on reduction of operation and maintenance costs which are viable for most renewable energy power systems, the energy cost would be $0.2/kwh which is affordable to the rural dwellers. (Munuswamy et al, 2011), compared the cost of electricity from fuel cell-based generated electricity to the cost of supply from the national grid for health centres in rural India. Their simulation result showed that “beyond a distance of 44km from the grid, the cost of supply from an off-grid source is cheaper”. (Rohit Sen & Subhes C.B, 2013), investigated the feasibility of an off-grid system powered by renewable sources in India using HOMER as their simulation software. They identified the optimal system and compared their system with the grid connected base. Their conclusion is that a hybrid combination of renewables for off-grid electrification is a cost effective alternative to grid extension.

In all of the research work mentioned above, the optimal design has been found by minimizing the total cost function while satisfying certain constraints such as, loss of load probability and the state of charge of the battery. (Ranaweera, June 2013), stated in his thesis research: that the accuracy of the final optimal design and the number of possible combinations that can be taken for the analysis are dependent on the method used for the minimization of the objective function. One of the major weaknesses of these methods is that they have not considered the effect of possible changes in the fuel price in the future, temperature variation, change of solar irradiance level due to climate change impact on the environment for the case locations and also the huge impact demand-side management can have on the feasibility of the project (such as the elimination of the operation and the maintenance cost). Also, most of the works on literature did not calculated the $CO_2$ emission to the environment as well as $CO_2$ reduction incentive and carbon tax benefits. That is also an important issue to be considered in the case of hybrid systems using diesel backup generators. This work will focus on the determination of the best configuration of the hybrid systems in the form of an off grid power generation to achieve the objective of this project. HOMER PRO student version is the software used for the simulation analysis. HOMER PRO is the modification of the original HOMER software which most of the cited literatures used in their analysis. This modified software is capable of analyzing the data to be obtained using several sources and variables. Sensitivity analysis of the uncertainties regarding the system inputs will be performed (for temperature variation, fuel price changes and solar irradiance variation) to examine the best system that can supply the load at the most cost effective CAPEX and LCOE.

## 2.2 Mini-grid Development Landscape in Nigeria: Challenges and Achievements so far

Mini-grid development in Nigeria is enabled by an active economy and population growth coupled with policy and regulatory support. Relevant policy supporting off-grid and rural electrification can be traced back over a decade. More recently, there has been an increase in supportive policies, plans, and regulations. “For example, regulation of mini-grids in Nigeria is more supportive of market development than in most developing countries, where such policy is either less advanced or non-existent” (NESG & RMI, 2018). The Nigerian Electricity Regulatory Commission (NERC) mini-grid regulation in 2016 promotes cost-reflective tariffs and a fast-track process for obtaining permits and creates a unique opportunity for interconnected systems. Power systems under 100 kW do not require a permit, while the permitting process for systems between 100 kW and 1 MW is abbreviated from the mandatory license for large power projects. NERC regulation offers an explicit framework for mini-grid development in Nigeria and provides a mechanism for developers to more easily recover investments, enables development of underserved communities, and generally allows developers to access more commercially viable sites. The Electric Power Sector Reform Act (EPSRA, 2005) empowers the Federal Ministry of Power, Works and Housing (FMPWH) with the overall responsibility for formulating electric power policies, while the Rural Electrification Agency (REA) is responsible for the coordination and implementation of rural electrification strategies, under the supervision of FMPWH. The Nigerian Electricity Regulatory Commission (NERC) independently regulates the entire power sector including off-grid development. The commitment of the FGN towards ensuring the development of mini-grid energy solutions in both rural and urban Nigeria has been outlined in several official policies documents and plans, for example, the NEPP (2001), the ESPRA (2005), the NREEEP (2015), the RESIP (2016), NERC Mini Grid Regulation (2017), and the PSRP (2017). The biggest hindrance to these development, has been the implementation strategy and the lack of continuity in leadership in the case of a change in government.

In 2017, REA secured US $86 million (₦30.2 billion) through FGN budget allocation, under the 2016/2017 Capital Budget Provision. Since then, the REA has successfully contracted a total of 386 rural electrification projects across the six geopolitical zones, with 329 projects fully completed and 57 still ongoing. Under the Zonal Intervention Projects, REA has also been able to contract a total of 28 projects. The projects rate of completion is also commendable. Solar projects (mini-grids, street-lighting and standalone solar systems) contributing 107 projects (achieving 100% completion rate), and others – grid extension and injection substation projects – contributes 309 projects (with 81% completion) (NESG & RMI, 2018).

The REA also secured a US$350 million (N123 billion) loan from the World Bank to support the Nigerian Electrification Project (NEP). The NEP is an initiative of the FGN which aims to provide a pipeline of potential local investments and financial incentives to encourage the Nigerian off-grid market through the provision of detailed market data, grants, and technical assistance. US$150 million (N53 billion) of the total amount for the NEP will be used only for mini-grid systems development across the country (NESG & RMI, 2018). The Nigerian Energy Support Program was launched in 2013 by the FGN in partnership with the European Union and the German Government – to be implemented by the GIZ with a kin focus on energy efficiency and the understanding of the various factors that determines customers' ability to pay and consumption pattern. The Nigerian Energy Support Program (NESP) aims to improve the conditions for investments in renewable energy, energy efficiency and rural electrification in Nigeria (GIZ, NESP, 2018). The pilot phase of NESP was concluded in 2017. It included, mini-grid pilot project development, the appraisal of conditions in the sector and first advisory services to the FMPWH - with the development of six off-grid solar mini-grids stations in five partner states. The six mini-grid projects are currently operational and are estimated to provide 10,000 individuals with reliable access to electricity (NESP, 2018). During its second phase (2018–2020), NESP will further support the implementation and enforcement of an investor-friendly mini-grid framework, through its various unit – focusing on electrification planning, sustainable off-grid electrification and Energy Efficiency. The goal is to deploy, through local partners, large off-grid solar mini-grids that provide electricity services to 100,000 people and at least 400 businesses in rural Nigeria (NESP, 2018).

A good example of the progress made towards improved energy access and the transition towards more renewable in the Nigerian energy mix, was the commitment by the Federal Government of Nigeria (FGN) through the Energy Commission of Nigeria (ECN) – working in conjunction with United Nations Development Program (UNDP), in 2005. They released the Renewable Energy

Master Plan (REMP, 2005). The REMP articulates Nigeria's vision and road maps to provide an increasing role for RE in attaining SDG 7. A more detailed report of this plan was produced in 2012. In the 2012 report, it shows that the FGN seeks to increase the share of renewables in electricity generation from 13% in 2015 to 23% in 2025 and 36% by 2030. Also in 2005, the FGN setup the ESPRA Act of 2005, which established the guidelines that led the successful unbundling of the then nationalized 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 licenses 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) (NEPSR, 2005). The Rural Electrification Agency through some of their energy access campaigns like the Energizing Economies Initiative (EEI) has been able to power small businesses in various business districts in Nigeria. More details can be found in the second chapter of this report. FGN through its efforts and partnerships, have successfully added more generation capacities to the electricity grid. For example, on the 31st of January, 2019 – best generation output (9MW) so far this year and in the last five years was generated and transmitted (NERC, 2019). There has also been a significant off-grid generation of electricity totaling to the tune of 452KW as at 2018 and currently, 429 projects which includes off-grid electrification projects current carried out by the REA with more to follow with the passing of the 2019 national budget (REA, 2019). This signals progress, but it is still a far cry to the set target by Presidential Taskforce on Power in 2010 – which is to of have a total installed capacity of 40,000MW by 2020.

All these efforts by the government where meant to make things better at least for the end-user but so far, it has mostly been a failed effort – this is because the unbundling of the value chain at that point and in the way it was done was only going to hurt the poor end user. The licenses were issued against the advice of experts and with much skeptism from the public. Once the bidding was sealed, there was no room for competing businesses to provide alternative for the energy consumers. Till date, most Nigerians, as seen from the response gotten from field data collection in the course of these research, are not happy with the DISCOs for numerous reasons ranging from high and estimated tariff systems to unannounced blackouts and lack of prepaid meters. These issues have led to multiple protest against the poor level of energy access rate, the poor energy service delivery by the DISCOs and the monetization of darkness to the Nigerian people (see figure 8 below). These greatly affect not just residential homes but small business owners and especially small scale perishable food famers and frozen food business owners.

*Figure 8: Nigerians Protesting Against the Poor State of Electricity Access in the Lagos*


Source: Author

### 2.3 Nigeria Energy Situation Overview

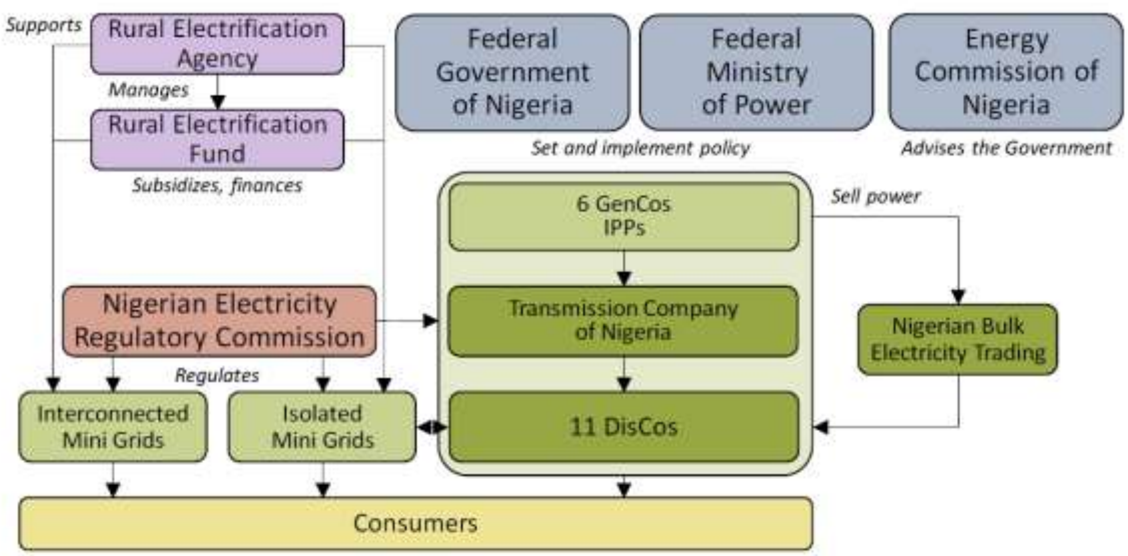
*Figure 9: Nigeria ESMAP Solar Resource Map*


Source: ESMAP, 2019

Nigeria is located in Sub-Sahara Africa and it is Africa's most populous nation according to the World Bank data, 2019. The population growth rate of Nigeria, based on World Bank records as at 1960 was at 1.8% but has increased to the rate of 2.6% per annum as at 2017 and currently has a population of about 186 million people. The World bank also reported in 2009, that 53.5% of the Nigerian population live on less than two dollars a day. This percentage of poverty rate is on the raise and is projected to have surpassed that of India from 2018 – reaching a status described as "multidimensional poverty" in 2019. IRENA renewable energy statistics report of 2018 states that Nigeria has 5750GWh of renewable energy production with a capacity of 2064MW at the year 2017 which translates to an increment of 2GWh in renewable energy production from the previous year. Furthermore, the IRENA report stated that the Nigerian Solar energy capacity was 19MW with a production rate of 26GWh as of the year 2016. Same IRENA 2018 report estimated the Solar Off-grid electrification capacity of Nigeria to be 0.800MW, while the total off-grid renewable capacity is estimated to be 21,740MW as of the year 2017 (IRENA, 2018). As seen in figure 8, most location in Nigeria, especially in Northern Nigeria has a solar horizontal irradiance of 5.4kWh per square meter and above. With proper planning and a good financial framework for energy developers, most of the off-grid renewable capacity can be met with solar photovoltaic.

### 2.3.1 Energy Sector Description and Power Generation in Nigeria

*Figure 10: Current Power Sector Structure in Nigeria*



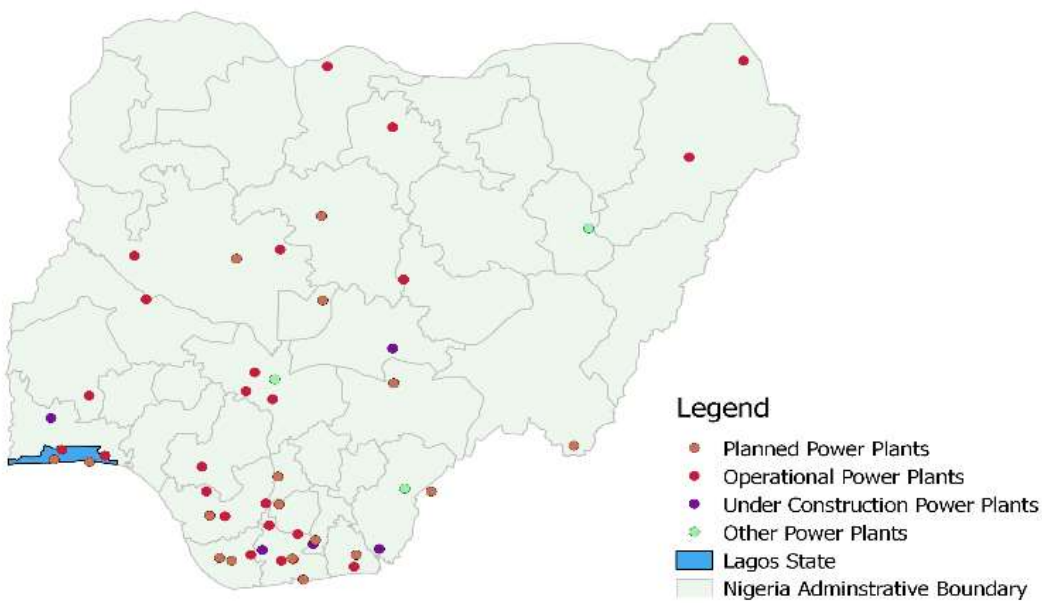

Source: ESMAP, 2017

In 2015, much of Nigeria's installed capacity was unavailable, due to poor transmission lines. The current energy generation capacity of Nigeria is about 12,500MW, as reported by the USAID, with an even less distribution capacity of about 4500MW; which could only meet approximately one-fourth of the estimated current demand for power from the grid (GIZ, 2015). This is clearly insufficient for a population of close to 200million people as at 2018. According to the Chairman of the Nigeria National Committee of the World Energy Council, Planning Experts estimate that for the Nigerian economy to grow at a rate of 10%, the country's electricity requirement must reach 30,000 MW by 2020, and 78,000 MW by 2030. According to the NERC, Nigeria has four power generation options. All of the options requires licensing as at 2015 except for the captive generation option –

which requires just a permit. The captive generation option, means that the electricity generated is entirely consumed by the generator itself, such option requires no Power Purchase Agreement (PPA) with any other external party (NERC, 2015). More recently, in other to encourage investment in off-grid mini-grid generation, the NERC no longer require developers to have a license for a generation capacity within 100kW power output. The generation options are listed below:

- Transmission based on-grid generation
- Embedded generation
- Off-grid generation
- Captive generation.

*Figure 11: A QGIS Map Representation of the Power Plants Network in Nigeria*




Source: World Bank 2017 Energy Data

World bank updated 2017 data report on the power plant statistics in Nigeria shows that most power generation is primarily from either gas-fired or hydro power plants. It can also be seen in QGIS from the attributes table of the data for figure 11 that natural gas is the main fuel source for power generation in Nigeria. (McKinsey, 2013) reported on the potential for energy generation in Nigeria from domestic gas reserve and stated that as at 2013, the gas reserve was greater than 10,000 MW. No other African country has a higher gas reserve potential.

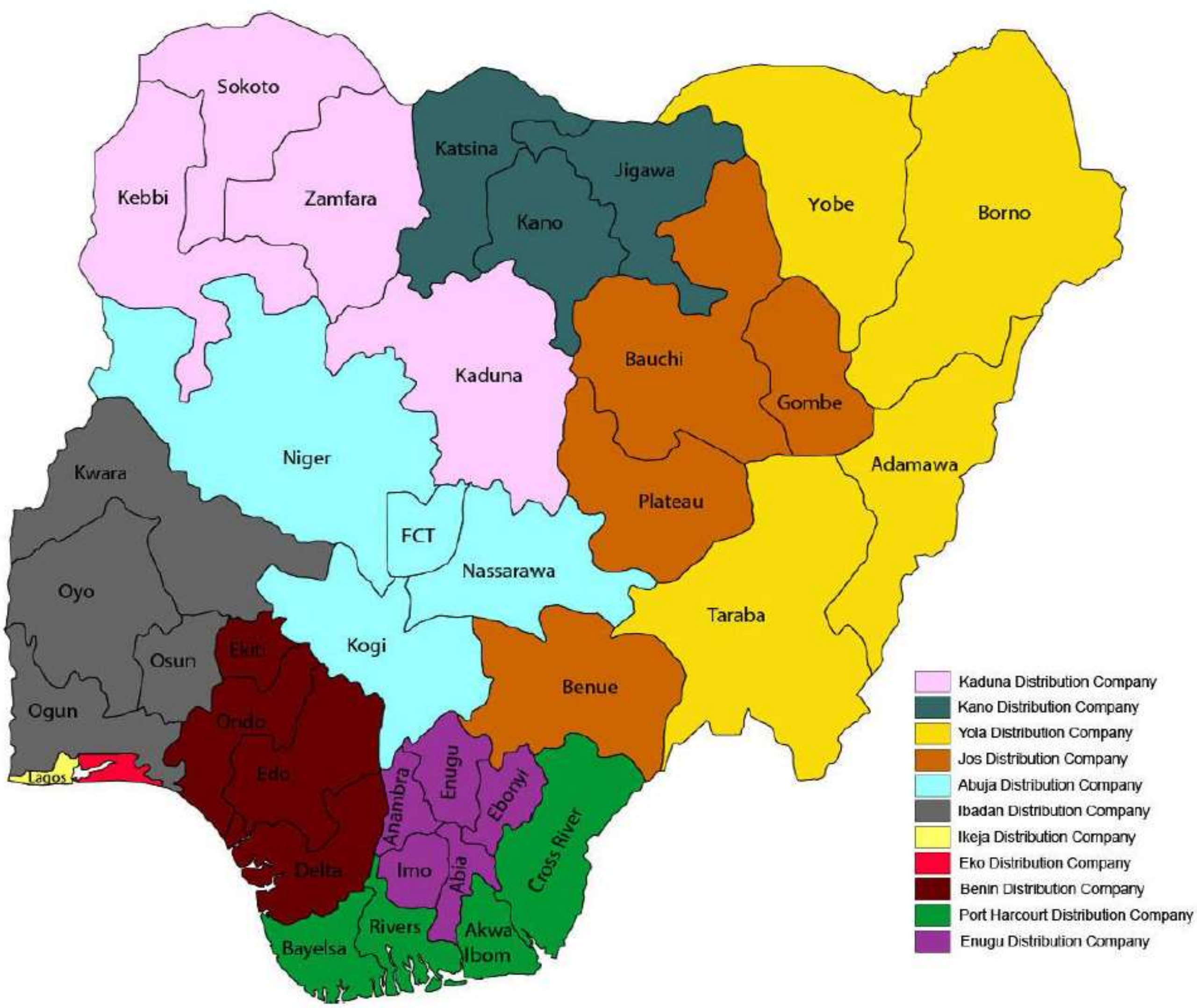
From the World Bank updated data on the status of power plants in Nigeria in 2017, it revealed that currently, Nigeria has an estimated 90 power generating stations (bot operational, planned and under construction) totally a power output of 27438.371MW. Hydro powered power plants make up about 11% of the total while Gas fired power plants makes up the rest 88.9%. the total estimated output of the gas fired (thermal) power plants is at 16134.971MW (for both the operational, planned and under construction). The operation power plants for both hydro and gas fired total output according to the data was 8972.544MW. It is also worthy of note that all of this power plants recorded are grid connected and the full generating capacity of Nigeria currently as around 12500MW and consist of both off-grid and on-grid power generation. The generation companies created following the unbundling of PHCN are: Afam Power Plc, gas fired; with a capacity of 776MW and currently 100% privatized. Sapele Power Plc, gas fired; with a capacity of 414MW and 51% sold to private owners. Egbin Power Plc, gas fired; with a capacity of 1,020MW and completely privatized. Ughelli Power Plc, gas fired; with a capacity of 900MW and completely privatized. Kainji Power Plant, hydro powered; with a capacity of 760MW, currently still be managed by the government but under a long term concession for privatization. Jebba Power Plant, hydro powered; with a capacity 578MW, currently still be managed by the government but under a long term concession for privatization. Shiroro Power Plc, hydro powered; with a capacity of 600MW, currently still managed by the government but under a long term concession for privatization (NERC Archive, 2019).

According to the (NERC Archive, 2019), Nigeria's generation sub-sector currently includes 23 grid-connected generating plants which are under operation, with a total installed capacity of 10,396 MW (available capacity of 6,056 MW) with thermal based generation having an installed capacity of 8,457.6MW (available capacity of 4,996 MW) and hydropower having 1,938.4 MW of total installed capacity with an available capacity of 1,060 MW. The sub-sectors comprise of the privatized GENCOs, Independent Power Producers (IPPs) and the generating stations under the National Integrated Power Project (NIPP). NERC in their archive defined IPPs as "power plants managed by the private sector prior to the privatization process. These include Shell operated – Afam VI (642MW), Agip operated – Okpai (480MW), Ibom Power, NESCO and AES Barges (270MW)" (NERC Archive, 2019). The definition of IPPs has grown to become broader than that and now includes off-grid mini-grid developers and power stations. The FGN incorporated the Niger Delta Power Holding Company (NDPHC) as a public sector funded emergency intervention scheme, with the mandate to manage the National Integrated Power Projects (NIPP). The objectives of the NIPP includes to help in the construction of identified critical infrastructure in the generation, transmission, distribution and natural gas supply sub-sectors of the electric power value chain. NDPHC plans to add ten new gas fired power stations to the grid some of which are highlighted in figure 11 below and some have been completed and commissioned, while others are still under construction. NIPP projects is expected to add a total of about 4,774MW of power to the national grid network after completion. Some of NIPP stations are listed (NERC Archive, 2019): Alaoji – capacity 1,074MW in Abia state, Benin (Ihovbor) – capacity 451MW in Edo state, Calabar – capacity 563MW in Cross River State, Egbema – capacity 338 MW in Imo State, Gbarain – capacity 225 MW in Bayelsa State, Geregu – capacity 434 MW in Kogi State, Omotosho – capacity 451 MW in Ondo State, Omoku – capacity 225MW in Rivers State.

## 2.4 Current Status of Electricity Sector in Nigeria

Electricity in Nigeria dates back to 1896. The first generation of electricity was in Lagos and the total power of the generators used then was 60kW. (Niger Power Review, 1985; O. I. Okoro & E. Chikuni, 2007). The Nigerian government electricity undertaking was established in 1946, under the jurisdiction of the Public Works Department (PWD) and was put in charge of electricity generation in Lagos, Nigeria. A more central body for the management of the electricity distribution in the country was established in 1950 and it was known then as the Electricity Corporation of Nigeria, (ECN). The Niger Dams Authority (NDA) was established by an Act of Parliament. NDA was responsible for the construction, maintenance of hydro dams and generating electricity NDA also sold the energy they produce to ECN for distribution. ECN and NDA came together to become one entity known as National Electric Power Authority (NEPA) in 1972 (O. I. Okoro & E. Chikuni, 2007).

*Figure 12: Nigeria Distribution Network Division by DISCOs*




Sources: NERC, 2019

Despite the expanding influence of the NEPA and the consequent privatization (in order to meet the ever-increasing energy demand of the people) that came in 2004, unfortunately, majority of Nigerians have no access to electricity and the supply to those provided is not regular. It is against this backdrop that the Federal Government embarked on aggressive power sector reforms with the intention of deregulating the power sector and making it more efficient and responsive to the demand of the Nigerian people, based on the Nigerian Energy Policy report from 2003 – that led to the power sector reform act in 2005. Once the Act was passed into law; automatically, all assets and liabilities of NEPA was transferred to PHCN. PHCN was subsequently unbundled into one transmission company (TCN), six generating companies, GENCOs, and eleven distribution companies, DISCOs. The GENCOs is now completely privately owned by individuals and the public while about 60% of the shares in the DISCOs is now owned by private operators. The transmission company of Nigeria is still 100% owned by FGN. Manitoba Hydro International (Canada) is responsible for revamping TCN to achieve and provide stable transmission of power without system failure (NERC Archive, 2019). It is clear by now that the Manitoba firm failed miserably in their task as a new deal has been signed and a new contract awarded to Siemens GbmH of Germany to help with the improvement of the transmission lines of Nigeria to a capacity of 11,000MW by 2023 (CNBC Africa, 2019).

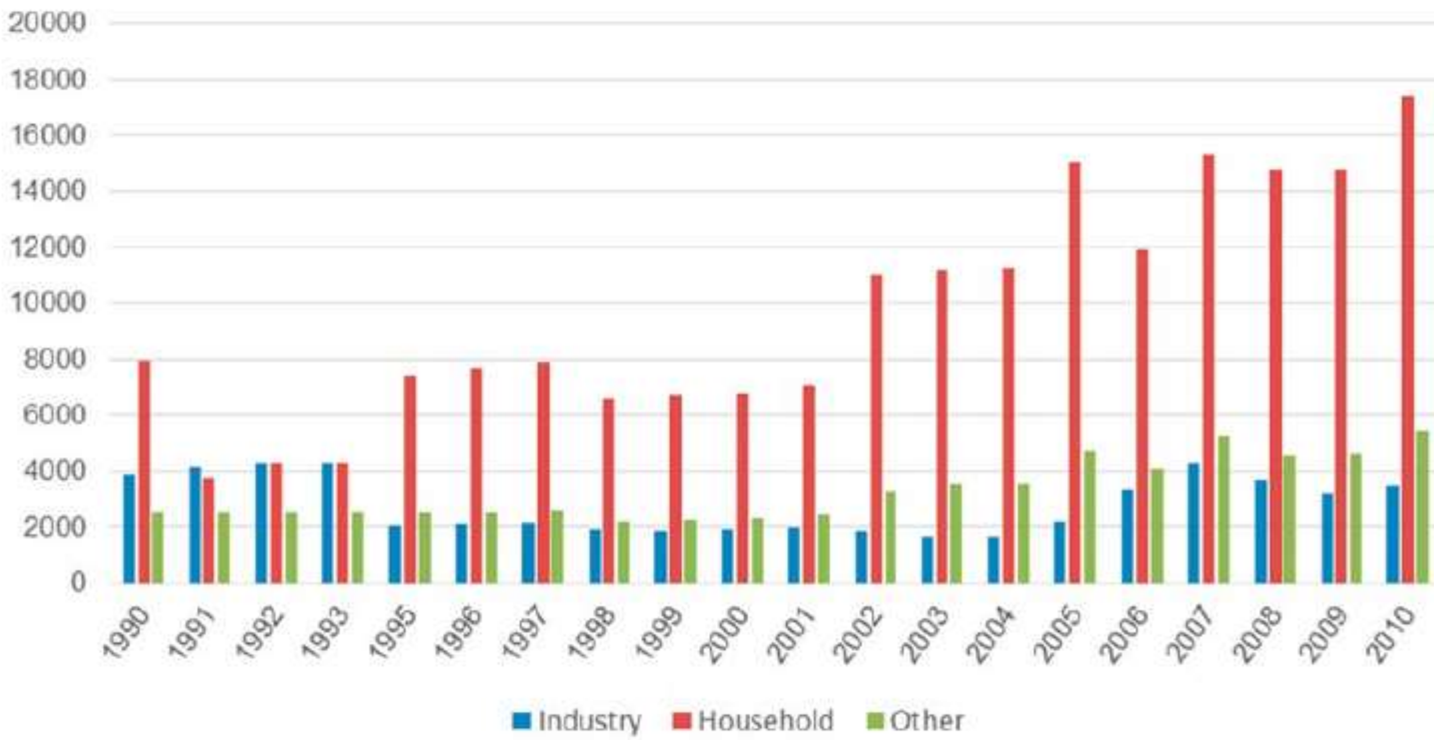
## 2.5 Electricity Consumption and Demand in Nigeria

*Table 2: Energy generation and supply profile in Nigeria*

| Year | Average Gen. Available (MW) | Max. Peak Generation (MW) | Maximum daily energy generated (MWh) | Total energy generated (MWh) | Total energy sent out (MWh) | Per Capita Energy Supply |
|---|---|---|---|---|---|---|
| 2007 | 3,781.30 | 3,599.60 | 77,322.30 | 22,519,330.50 | 21,546,192.20 | 155.3 |
| 2008 | 3,918 | 3,595.90 | 86,564.90 | 18,058,894.90 | 17,545,382.50 | 120.4 |
| 2009 | 4,401.80 | 3,710.00 | 82,652.30 | 18,904,588.90 | 18,342,034.70 | 122.00 |
| 2010 | 4,030.50 | 4,333.00 | 85,457.50 | 24,556,331.50 | 23,939,898.90 | 153.50 |
| 2011 | 4,435.80 | 4,089.30 | 90,315.30 | 27,521,772.50 | 26,766,992.00 | 165.80 |
| 2012 | 5,251.60 | 4,517.60 | 97,781.00 | 29,240,239.20 | 28,699,300.80 | 176.40 |
| 2013 | 5,150.60 | 4,458.20 | 98,619.00 | 29,537,539.40 | 28,837,199.80 | 181.40 |
| 2014 | 6,158.40 | 4,395.20 | 98,893.80 | 29,697,360.10 | 29,013,501.00 | 167.60 |

Source: NERC Archive, GIZ, 2015

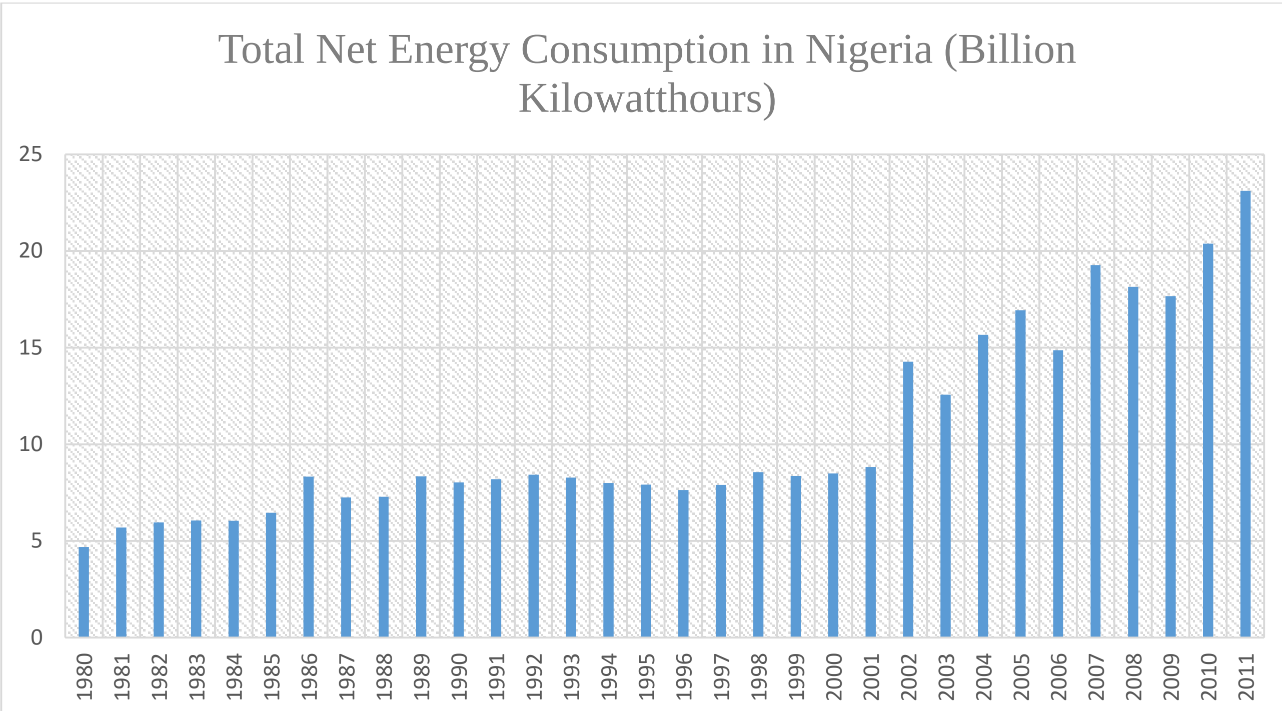
*Figure 13: Nigeria Electricity Consumption by Sector (Million kWh)*




Source: IEA Energy Statistics

The Nigerian population and its economy keeps growing at a fast rate. This has resulted to an ever increasing demand for electricity. This demand is projected to continuously be on the rise and the only feasible means to keep up with this rise in energy demand is to tap into all the available energy resources in Nigeria, especially the off-grid mini-grid solutions. In Nigeria, the average annual per capita power consumption is at 155 kWh as at 2018, which is among the lowest in the world and even lower than most of the previously reported peak annual average per capita as seen in table 2 above (NERC, 2018). The data from the Nigeria NBS open data archive shows a steady increase in energy demand forecast as illustrated in the figure 14. Figure 13 shows a strong increase in the yearly electricity consumption, mainly driven by residential consumption. The electricity consumption data available on Nigeria by sector according to the IEA reveals that it is the residential sector that consumes by far the most energy (IEA Energy Statistics, 2015).  According to the World Bank's projection, electricity demand is to grow by a factor of over 5 until 2035 up to almost 530 TWh (GIZ Nigeria, 2015).

*Figure 14: Total Net Energy Consumption in Nigeria (Billion kWh)*

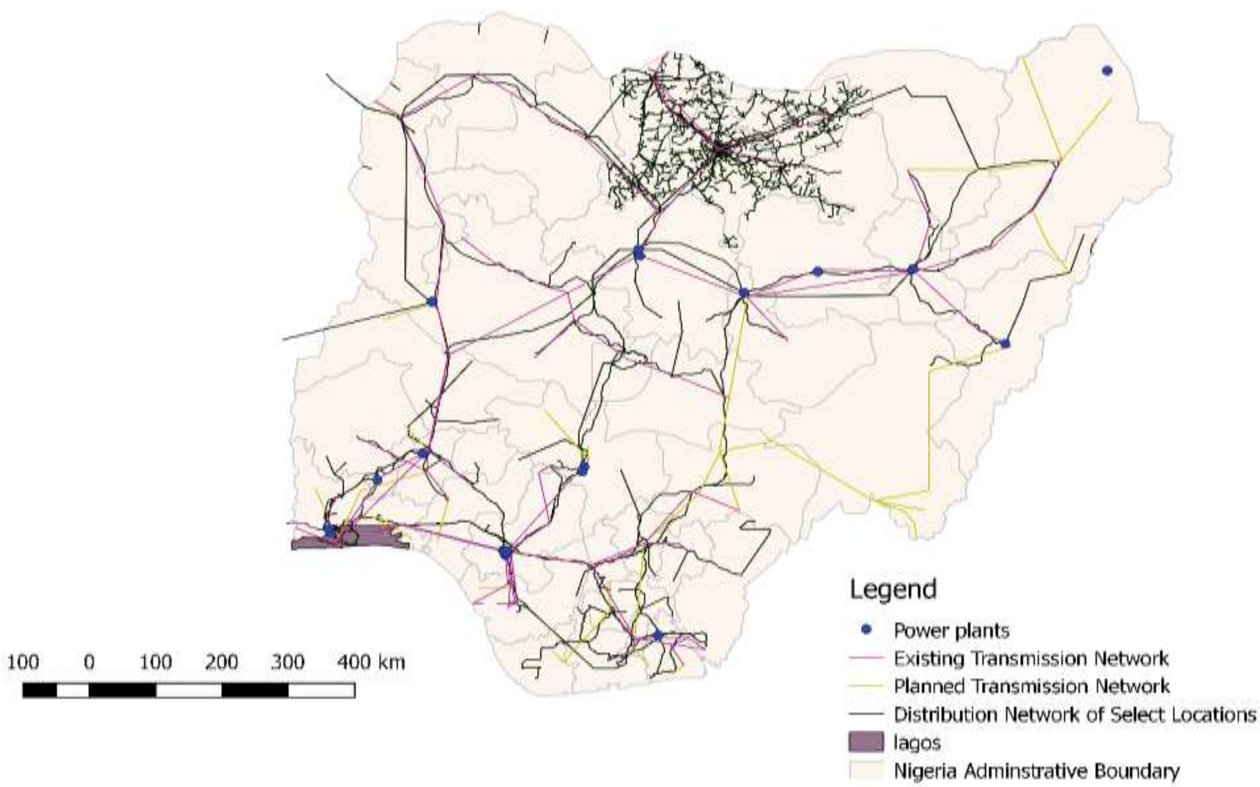



Source: NBS, 2011

The Renewable Energy Master Plan provides the most detailed demand projections and estimates a peak power demand in 2020 of approximately 45,490 MW (REMP roadmap, 2015). For all cases, generation capacity has to be increased significantly, and in light of this reality, research work like this work is important to future energy landscape of Nigeria. Bearing these various scenarios in mind, it's imperative to see reason in the fact that this thesis research is very important not just to national economic growth but in fact national security. We can see that from all indication, the current energy demand will even grow with time and there is therefore an urgent need to have not only a solution but a sustainable and cost effective solution. The mini-grid solution is also supported by the (EIA 2017 report), which recommends that micro-financed mini-grid power generation provides the best cost effective alternative to energy access deployment in emerging economies.

## 2.6 Electricity Distribution and Transmission in Nigeria

*Figure 15: QGIS Map Representation of the Transmission and Distribution Network in Nigeria*

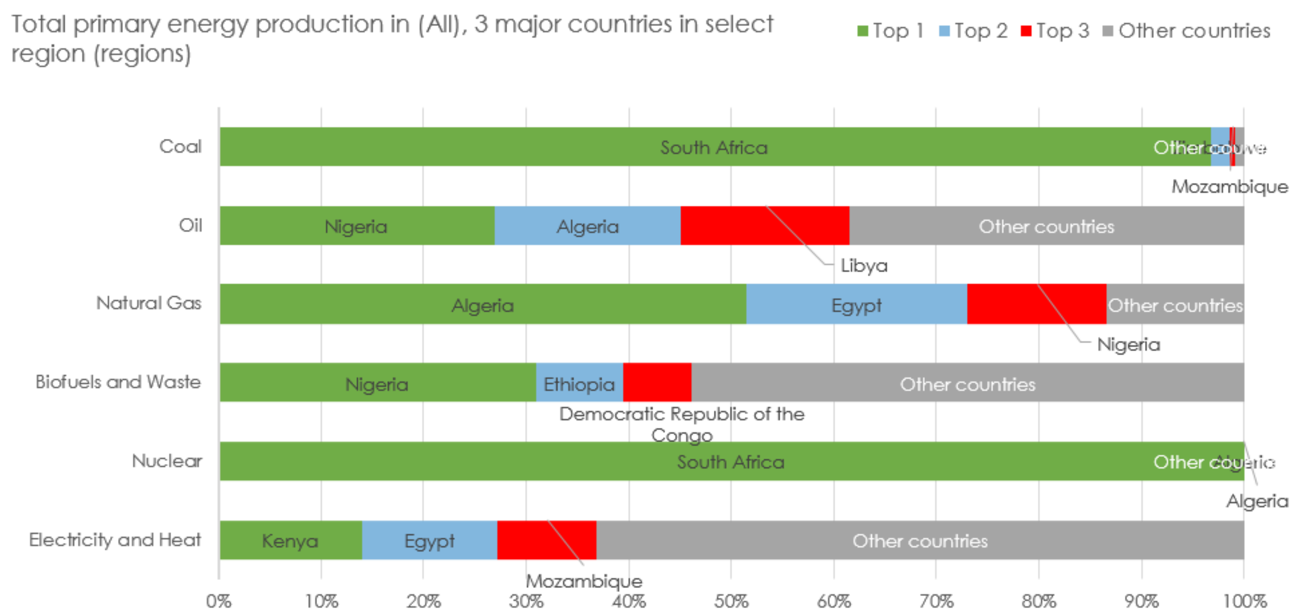



Source: Energy Open Data website, 2019

The Nigerian distribution grid as shown in figure 15, goes directly to consumers for both domestic and productive use. It operates mainly on 33 kV and 11 kV level, (medium voltage (MV) and low voltage level (LV) respectively). The National transmission grid operates at 330 kV and 132 kV high voltage level (HV). The (GIZ, 2015), reported in their Nigerian energy sector report that in 2010, "more than 12,300 km of transmission lines (5,523 km of 330 kV and 6,801 km of 132kV) connecting 32 330 kV and 105 132 KV sub-stations were operational". TCN is responsible for electricity transmission, system operation and electricity trading in Nigeria by transmitting the electricity from the GENCOs to DISCOs. A more recent publication on NERC Archive website, states that the TCN's transmission wheeling capacity is at 7,500MW and over 20,000km of transmission lines. NERC also stated that the transmission current capacity of 5,300MW is higher than average operational generation capacity of 3,879MW but it is far below the total installed generation capacity of 12,522MW. NERC reports that on the average, an approx. of 7.4% of losses in energy transmission occurs across the network and its much higher, when compared to emerging countries' loss levels of 2-6% (NERC Archive, 2019). There are plans by the FGN for transmission grid expansion and even recently signing a deal with Siemens GmbH to support the FGN grid expansion plan to a capacity of 11000MW by the year 2023. (NERC; Feb 2011) in a 2011 report, stated that in 2010 more than 24,000 km of distribution network were available in Nigeria. Figure 15 shows the Nigerian states covered by a few distribution networks and the transmission lines.

## 2.7 Domestic and Productive Energy usage in Nigeria

*Figure 16: Total primary energy production in Nigeria and other select countries*




Source: UN Energy Statistics

Domestic energy usage in Nigeria is mostly for cooking. The household cooking sector is the largest consumer of energy in Nigeria according to IEA energy statistic; using around 80% of the total, 90% of which is derived from biomass, particularly fuel wood as seen in figure 16 above. The second biggest sector that uses energy in Nigeria is the industries which is considered as productive usage of electricity as it results to a significant contribution to the GDP of the country. Other sources of cooking energy are used in Nigeria, including liquefied petroleum gas, kerosene, and electricity, but they are expensive compared to biomass, which is available at little or no cost. With majority of the Nigerian population according to the World Bank recent poverty index report, earning less than $1 per day (World Bank Poverty index, 2019), biomass stands as the preferred source of household cooking energy in Nigeria. The other possible cost effective alternative to residential energy consumption is electricity but the poor access to electricity in Nigeria is a major challenge, especially in rural communities. Currently only about 39% of the rural population in Nigeria has access to electricity; consequently, eliminating electricity as a source of cooking energy for more than 60% of the rural population. (Nasiru, I.M, 2015) stated in his desertification report, that the increasing demand of fuel wood for domestic energy supply has led to the increase with the rate of deforestation, which contributes to desertification in some parts of the country, majorly the Northern parts. The Food and Agriculture Organization (FAO, 2005) estimates Nigeria's annual deforestation rate to be around 3% per year. At this particular rate of 3%, it is estimated that Nigeria is losing about 410,000 hectares of forested land annually, which can lead to increase in soil erosion impact on the environment and especially harm farmers. The effects of indoor air pollution from burning biomass in open fires for cooking in most Nigeria homes is of huge concern. (Smith, K.R & Mehta, S, 2003) reported that indoor air pollution can lead to respiratory diseases and premature deaths. Clearly, the major source of domestic energy use (even though sustainable) is not climate worth, or healthy. From field data collection, survey has shown that people are willing to change if only they will be given an affordable and much better alternative. The experience is similar in the business environment where our current research is focused. Most energy consumption comes from either the grid (PHCN which is majorly powered by gas) or from standalone generators. The feedback from the business owners shows a one hundred percent (100%) acceptance to alternative energy choice that is affordable and even in some cases that cost just as much as what they are currently paying for electricity.

## 2.8 Renewable Energy Potential in Nigeria

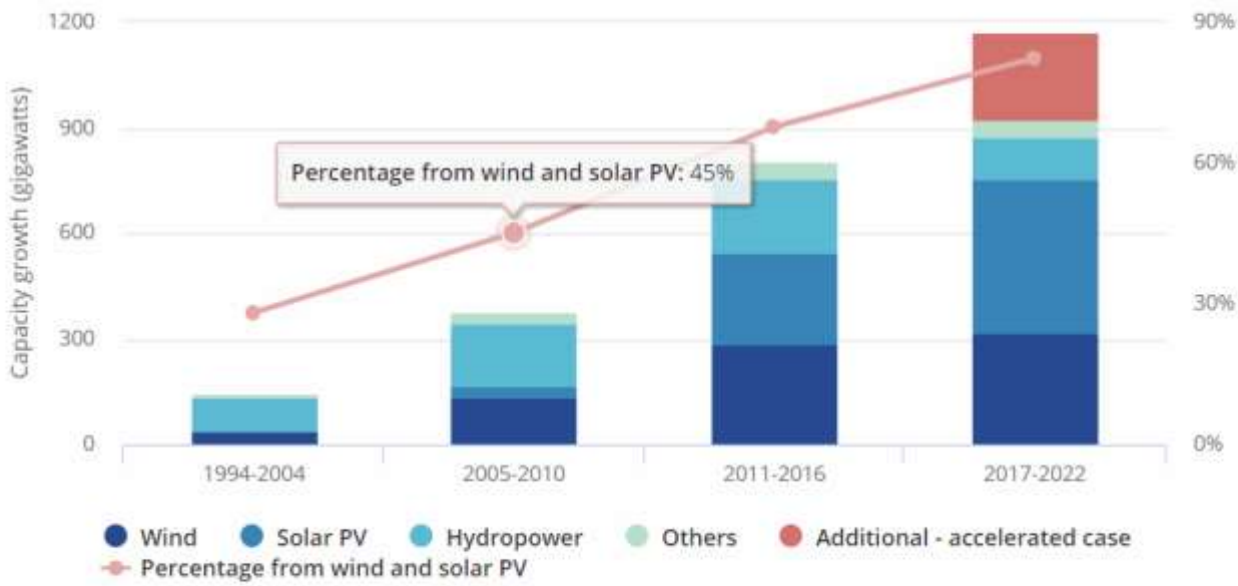
*Table 3: Renewable Energy Potentials in Nigeria*

| Resource type | Reserves | | | Production | Domestic utilization (natural units) |
|---|---|---|---|---|---|
| | Natural units | | Energy units (Btoe) | | |
| Small Hydropower | 3500 MW | | 0.34 (over 40 years) | 30 MW | 30 MW |
| Large Hydropower | 11,250 MW | | 0.8 (over 40 years) | 1938 MW | 1938 MW |
| Wind | 2–4 m/s at 10 m height (main land) | | 0.0003 (4 m/s @ 12% probability, 70 m height, 20 m rotor, 0.1% land area, 40 years | – | – |
| Solar Radiation | 3.5–7.0 kWh/m$^2$/day (4.2 million MWh/day using 0.1% land area) | | 5.2 (40 years and 0.1% land area) | 6 MWh/day | 6 MWh/day |
| Biomass | | | | | |
| Fuel wood | 11 million hectares of forest and wood land | Excess of 1.2 m ton/day | – | 0.120 million ton/day | 0.120 million ton/day |
| Animal waste | 211 million assorted animals | | | 0.781 million ton of waste/day | None |
| Energy crops and agric residue | 28.2 million hectares of arable land (≡ 30% of total land) | | | 0.256 million ton of assorted crops/day | None |

Source: Renewable Energy Master Plan (2009); M. Shaaban, J.O. Petinrin, (2014)

According to IEA renewable energy statistic 2017, renewable energy sources contributed almost two-thirds of net new power capacity around the world in 2016, with about 165 gigawatts (GW) power output in total, with majority coming from solar and wind as seen in figure 17 below (IEA renewables, 2017). IRENA 2030 African renewable energy roadmap states that renewables can play a transformative role in the African energy mix because of the abundant combination of fossil fuels and renewable sources in many countries on the continent (IRENA 2030 Africa roadmap, 2017). Assuming government policies that are targeted towards lifting the barriers to renewable energy growth are fully implemented all over the world, IEA projection analysis reports that global renewable capacity growth (led by China) could be boosted by another 30%, leading to an extra 1,150 GW by 2022. The prices of crude oil have been growing in more recent year but still very volatile. For the African continent, in other to survive the future, there is an urgent need to shift to other energy sources; as a matter of continental energy security.

*Figure 17: Renewable Electricity capacity growth forecast*




Source: IEA renewables, 2017

In Nigeria, renewable energy resource development has the potential to bridge the major energy gaps in rural areas, particularly Northern Nigeria. The scale of opportunities is only just becoming apparent as new grid technologies such as concentrated solar power are emerging as in competitors with conventional power generation. In a study on renewable energy potentials in Nigeria by (Chris Newsom, 2012) he stated that concentrated solar thermal power potential in Nigeria are at over 427,000MW. The fact that the current power generation capacity of Nigeria is below current demand, renewable energy alternative is well positioned to make up for the huge energy deficit in the country.

### 2. 8.1 Wind Energy Potential in Nigeria

Wind energy generation is the fastest growing renewable energy market worldwide (IEA renewable report, 2017). The Global Energy Wind Council (GWEC) using their models predict that installed wind power capacity in Africa will rise to between 75 GW and 86 GW by 2030 (GWEC, 2014). (IRENA, 2015b) reported that by the end of 2013, total installed wind capacity in Africa was 1,463 MW. In 2014, 999 MW of new capacity was installed, bringing the total to 2,462 MW at the end of 2014. According to (M. Shaaban, J.O. Petinrin, 2014), wind speed in Nigeria ranges from 4.0 to 5.12 m/s in the extreme northern part of the country, while 1.4–3.0 m/s in the southern Nigeria. ECN carried out a study to determine the wind potential of some regions in Nigeria in 2004 and the studies revealed that the total exploitable wind energy reserve at 10m height may vary from 8 MWh/year in Yola to 51 MWh/year in the mountainous area of Jos, and could reach as high as 97 MWh/year in Sokoto. Despite the low wind speed in some areas in Nigeria, wind power plants can still be employed for standalone power generating systems using small scale wind turbines. There have been some efforts made in this direction, with wind power station development commissioned by the federal government of Nigeria in partnership with foreign investors. Currently in the northern region of

Katsina state, a mini-grid wind powered station of 10MW capacity is current being completed and will be commissioned in October, 2019 (FMPHW report, 2019). IRENA 2015 African 2030 roadmap stated that "many projects in Africa will require considerable additional investments to bring power from the best wind locations to biggest demand centres, which can raise supply costs by USD 0.05 to USD 0.20 per kWh". This is one of the numerous challenges that is currently inhibiting the development of wind energy resource in Africa.

### 2.8.2 Biomass & Biofuel Energy Potential in Nigeria

Biomass is a significant renewable energy resources because of its availability and cost, but the sustainability of its production is of concern and should be properly considered whenever it is used. Biomass is an indirect form of solar energy because it arises due to photosynthesis. Nigeria has an abundance of biomass and biofuel raw material such as wood, shrubs, wastes arising from forestry, agricultural and also waste from industrial activities. Nigeria's biomass resource is estimated at $8x10^2$ MJ (M. Shaaban, J.O. Petinrin, 2014). (Garba B, Bashir A, 2002) reported that for energy use, about 80 million $m^3$ of fuelwood is utilized annually in Nigeria for cooking and other domestic purposes. (Oyedopo S. O, 2012) in his work on energy for sustainable development in Nigeria stated that 200 million ton of dry biomass can be obtained from forage grasses and shrubs, and its capable of releasing about 2.28 106 MJ of energy. NBS estimate that Nigerian total national energy demand as at year 2000, was 39 million ton of fuelwood. From table 3 its show that Nigeria has a reserve of 11 million hectares of forest and wood land which is capable of generating up to 0.120 million ton/day of Biomass/Biofuel resources and an animal waste of equivalent output. If the rate in which the use of biomass continues to increase, it will lead to more deforestation and even worse desertification. Therefore, the use of more fuelwood needs to be discouraged through the introduction of affordable and sustainable alternatives like Solar PV hybrid systems. The REMP (Renewable Energy Master Plan) has projected biomass to contribute 50MW of electricity in the medium term set at year 2015 and 450MW by 2025.

### 2.8.3 Hydro Energy Potential in Nigeria

Hydro power resources are abundant in Africa. IRENA and IEA estimates that 92% of power generation potential in Africa is still unexploited. (IRENA and IEA-ETSAP, 2015b). The above statistics reported by IRENA makes hydro power the most significant renewable power generation option currently deployed in Africa. Hydro power generation currently constitute about 2% of the total world energy mix out of the total global 5% from all renewable energy sources (IEA renewable, 2017). (Bada H. A, 2011) in his article in 2011 reported that global hydropower capacity in 2004 was 2810 TWh and that it was projected to be 4903 TWh by the year 2030, with 1.8% growth rate per year. The total potential reserve of hydropower in Nigeria according to the (REMP, 2009) is about 11,350 MW as show in table 3 above and only 1930 MW, about 14%, of that is currently being generated at Shiroro, Kanji and Jebba representing about 10% of total installed grid-connected electricity generation capacity of Nigeria considering both planned, under construction and operational power plants in Nigeria. Hydropower is currently the second major source of electric power generation in Nigeria, following gas fired power plants which constitute about 89% of the grid-connected power generation in Nigeria.

### 2.8.4 Solar Energy Potential in Nigeria

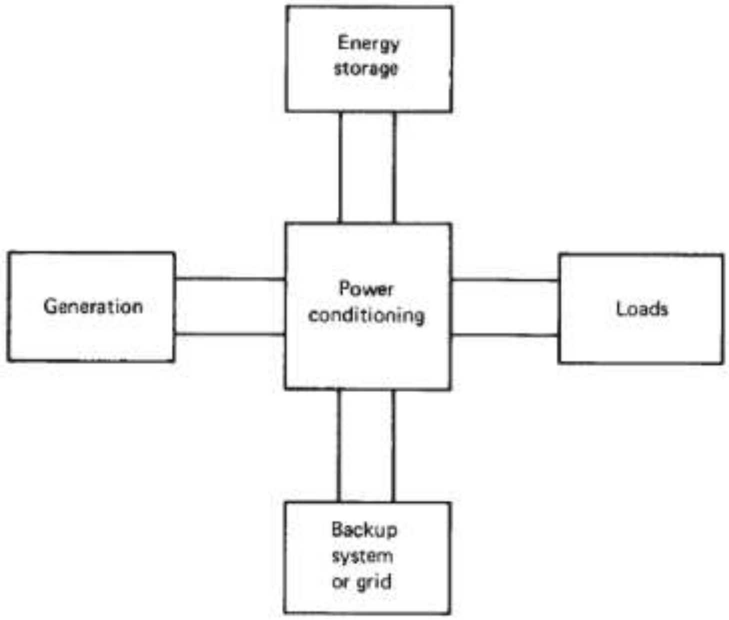
Africa's solar PV capacity has grown exponentially in recent years. IRENA 2015 report stated that total solar energy installed capacity in Africa at the end of 2014 was 1,334 megawatt (MW), which is over ten times larger than the reported output of 127MW in 2009. (Augustine C and Nnabuchi M, 2009) stated in their article that Nigeria has an average of 1.804 1015 kWh of incident solar energy annually. Using the total administrative boundary land area of about 924 103 km2 for Nigeria and an average of 5.535 kWh/ m2 /day and the sun shining on an average for 6.5 h/day. They calculated annual solar energy output value for Nigeria to be about 27 times the country's total fossil energy resources in energy units and over 115,000 times the electrical power produced in 2009, Even when the efficiency level of the cells is factored in, let say at 18% of the possible power output, with a capacity factor of zero percent. The sun radiates about 3.8 1023 kW of energy daily, which is 1.082 million ton of oil equivalent (mtoe) per day (Sambo A, 2005). This energy radiation from the sun is about 4000 times the current daily crude oil production in Nigeria and about 13,000 times the natural gas daily production, based on standard energy units (Idigbe K and Onohaebi S, 2009). This clearly highlights the importance solar energy as an energy source in Africa and for Nigeria in particular. Figure 9 above shows that majority of the location in Nigeria is very much suitable for the development of a solar power generation station – with an average solar irradiance of over 5kWh/square meter. It is in the interest of the Nigeria government and most especially Nigeria MSMEs that solar energy potentials are fully harnessed in the fight towards 100% cost effective and sustainable energy access rate in the country.

## 2.9 Renewable Energy Systems

### 2.9.1 Solar Photovoltaic Systems

Conventional Photovoltaic system may consist of the solar cells, a storage system, a backup (generator or grid connected) and an electrical load (ac or dc). Solar cells generate dc outputs and because electrical power is mostly utilized in ac form, the solar PV system will need some form of power conditioning between the solar cell modules and the electrical load, especially when the system becomes more complex like a mini-grid. The equipment that are used for this conditioning in other to ensure system stability are: Inverters, Rectifiers etc. – they also provide an interface between the different system elements. See the illustration in figure 18 below:

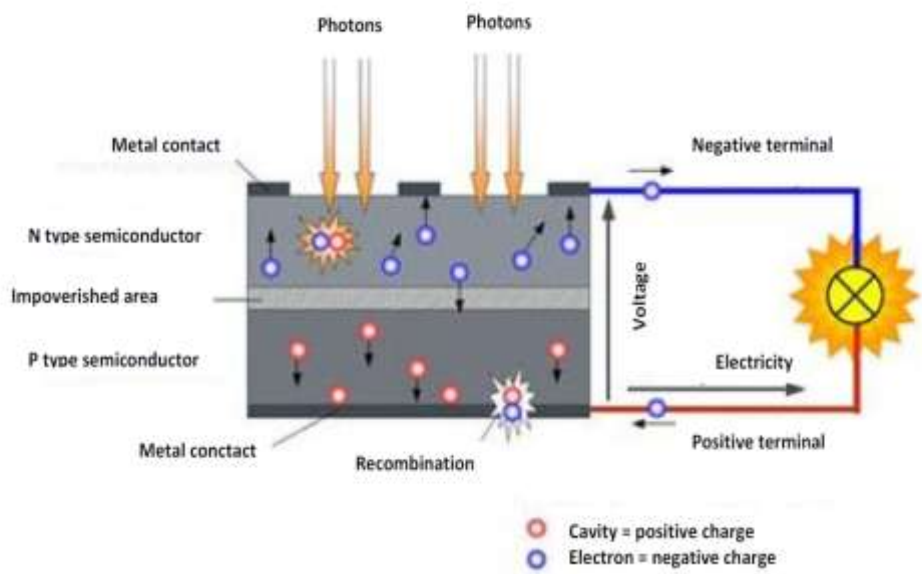
*Figure 18: Illustration of a general case of power conditioning in a solar photovoltaic*




Source: Solar Cells by Martin A. Green, 1982

Solar energy has an advantage over the other renewable options in that this resource because, it is more evenly distributed throughout the world. Furthermore, the amount of solar energy insolation in various locations in the world is well known with a greater certainty than are wind or hydro power resources. This makes it easier for developer to quickly identify suitable site for solar power station development and might not need a year of data collection in other to assess the extent of the resource before committing to a solar system. There are three basic types of PV systems: grid connected, standalone and hybrid/mini-grid PV systems. Standalone systems are mostly applicable in small scale applications such as solar home systems, used for provision of energy to small and large businesses, schools, hotels, hospitals etc. especially in isolated places. The grid connected systems mainly used for large scale solar power generation, hybrid/mini-grid systems and in some solar home systems where excess energy is sent to the grid and vice versa. The hybrid/mini-grid PV systems involve the use of a PV generation in combination with one or more renewable energy sources or even a non-renewable source like generators. One of the major drawbacks to the use of solar power for mini-grid system development is because of the cost of the equipment required to harness the energy of the sun before it can be converted to useful energy. That is why it takes a lot of analysis such as this work to determine the feasibility of siting a solar energy project (mini-grid) in a given location. The most recognized way of utilizing solar energy is the conversion of solar energy to electrical energy by PV installations. Photovoltaic cells are mainly manufactured from a semiconductor material called crystalline silicon, which is available abundantly in the earth’s crust. Solar photovoltaic modules, resulting from combination of photovoltaic cells to increase their power output. The efficiency of the system is dependent on various factors. These factors include both the solar cells material physical, chemical and the environmental characteristics of the site in which the PV system will be deployed. Most commercially available Photovoltaic cell in Nigeria has an efficiency of about 15 - 17%, with a lifetime of about 25 years. The systems (cell, module, and network) require minimal maintenance but it is important that routine inspection of the system is done periodically in other to identify parts that needs to be replaced early enough. Figure 19 below shows the schematic of a solar cell.

*Figure 19: Functioning of the Photovoltaic cell*




#### 2.9.1.1 PV power output calculation using HOMER Pro

The power output of a PV module is a function of the solar irradiance and the cell temperature and can be calculated using the following formula where cell temperature can be found using. The output of the PV array is calculated using the following equation.

$$P_{pv} = Y_{pv} f_{pv} \left[\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right] \left[1 + \propto_p (T_c - T_{c,STC})\right] \qquad (1)$$

Where:

| | |
|---|---|
| $P_{pv}$ | Rated capacity of the PV array, meaning its power output under standard test conditions (kW) |
| $f_{pv}$ | The PV derating factor (%) |
| $\bar{G}_T$ | The solar radiation incident on the PV array in the current time step ($kW/m^2$) |
| $\bar{G}_{T,STC}$ | The incident radiation at standard test conditions (1 $kW/m^2$) |
| $\propto_p$ | The temperature coefficient of power (%/°C) |
| $T_c$ | The PV cell temperature in the current time step (°C) |
| $T_{c,STC}$ | The PV cell temperature under standard test conditions (25°C) |

While modelling the system and the designer chose not to model the effect of temperature on the PV array, HOMER Pro assumes that the temperature coefficient of power is zero, so the equation above is simplified:

$$P_{pv} = Y_{pv} f_{pv} \left[ \frac{\bar{G}_T}{\bar{G}_{T,STC}} \right] \qquad (2)$$

### 2.9.2 Mini-Grid Energy Systems

A mini-grid system is small-scale electricity generating station that is used to supply energy to a limited load scale. Mini-grid can be connected to a distribution network or can be completely off-grid. Mini-grids can be categorized by size and this sizes are defined according to the Energy Sector Management Assistance Program in Kenya into three different categories (ESMAP Kenya, 2016):

1. > 1MW: – Independent power producers (IPP) that are usually grid-connected and sell most of their power to an anchor off-taker based on a power purchase agreement (PPA).

2. 100 kW – 1MW: – Delivered usually through a public model in which one authority is in charge of implementation of projects and a corporation is in charge of operation and maintenance.

3. < 100 kW: – Used in small but densely populated areas. They cover small radiuses with low voltage distribution. Some of them do not provide electricity at grid-quality level.

In Nigeria, a mini-grid system network is “any electricity supply system with its own power generation capacity, supplying electricity to more than one customer and which can operate in isolation from or be connected to a Distribution Licensee’s network with a generation capacity of between 100kW and 1MW” (NERC, 2017). Mini-grid sizing and design framework directly affects the cost structure of the project and determines the price and the quality of the energy produced (Arif Md. Waliullah Bhuiyan et.al, 2011). Lack of knowledge about the load conditions, electrical demand and future load growth during the sizing process can result in:

- Oversized mini-grid systems: Oversizing a mini-grid results in increased investment and thus higher payback times, as well as higher operational costs and lower overall efficiency. Over-sizing the diesel generator often leads to an operation below the recommended load factor and a low efficiency range. Furthermore, operating the diesel generator below the stated minimum load results in increased maintenance costs, in many cases even permanent damage. Furthermore, the operational mode of an oversized system leaves no space for PV-power feed in and leads to unnecessary energy losses.
- Undersized mini-grid systems: Under-sizing the mini-grid system results in an unreliable supply, leading to blackouts and reduced service quality. Unreliable supply will negatively affect customers and lead to a high dissatisfaction. Moreover, the technical components will suffer from the incorrect sizing, potentially leading to higher operation and maintenance

costs of the system. Regulatory issues may also arise when it comes to payments of the defined tariff for the provision of electricity if service quality is low.

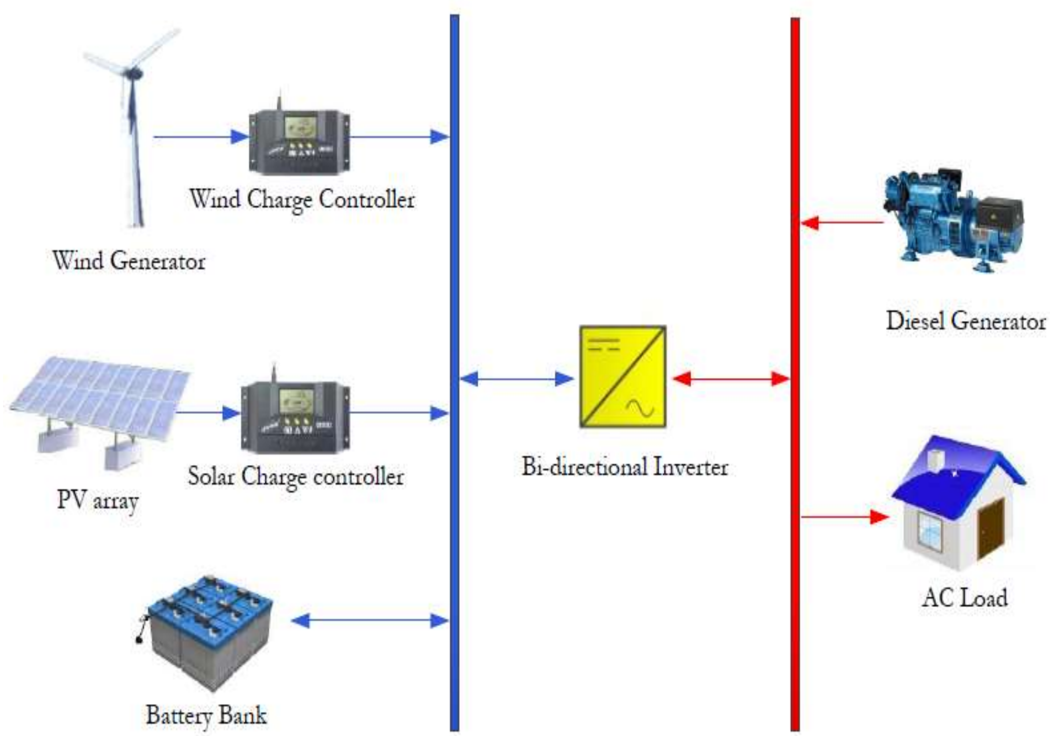
Both the case of under-sizing and oversizing, lead to an incorrect operation of mini-grids and lower quality of electricity supply at higher costs, a detailed electricity demand assessment and accurate system sizing are crucial. Demand assessment has a direct impact on the size of the components and thus the investment costs. Considering the characteristic of the assessed demand profile, peak demand hours and load profile characteristics can be evaluated. This is crucial for the process of choosing the right components in terms of size and specifying the operation mode of the mini-grid.

### 2.9.3 Hybrid Energy Systems

Hybrid energy systems generate AC electricity by combining renewable energy systems with an inverter, which can operate alternatively or in parallel with a conventional engine driven generator. Figure 20 below shows a schematic of a hybrid energy system. Hybrid systems can be classified according to the type of voltage and the type of bus that will link the different component together:

- DC coupled Hybrid system
- AC coupled hybrid system
- DC/AC coupled hybrid system

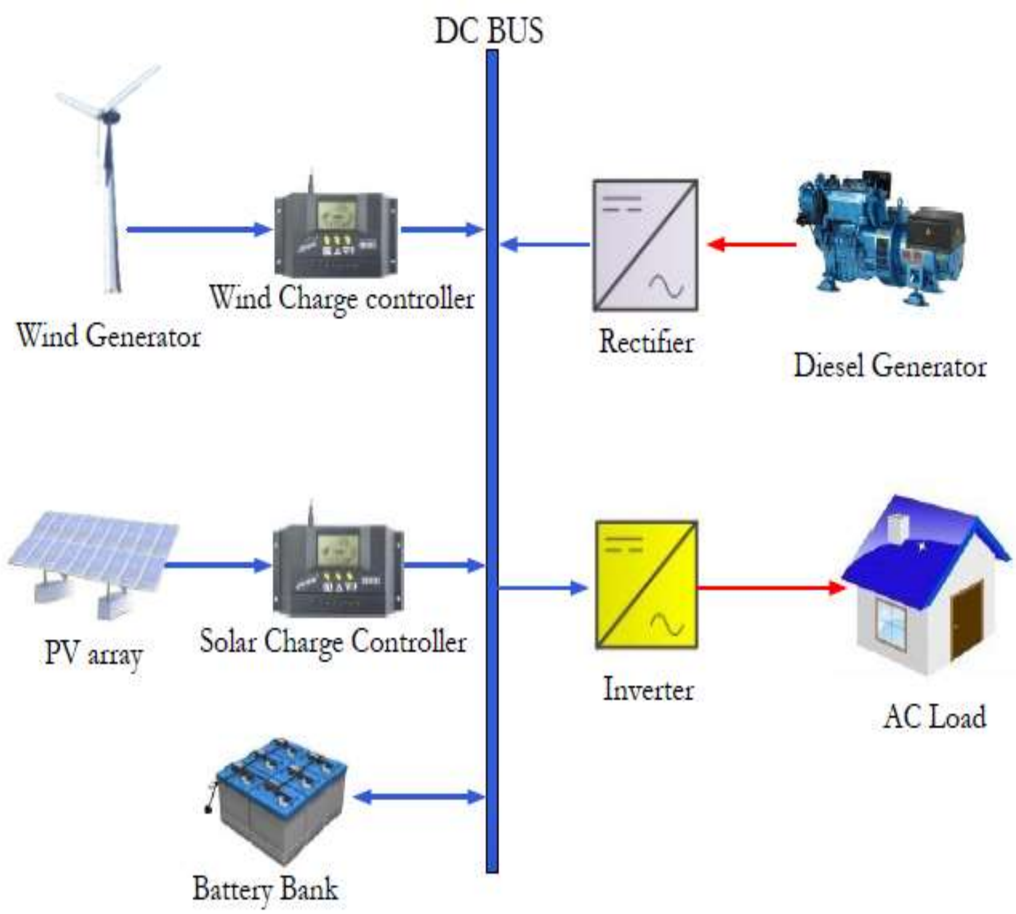
*Figure 20: Schematic representation of a hybrid energy system*




Source: (Ranaweera, June 2013)

**DC coupled Hybrid system:** In this configuration as shown in figure 21, all the electricity generating components are connected to one DC bus by means of a proper and highly efficient power electronic interfacing circuits. The power generated by the diesel generator is first rectified and then converted back to AC. This process has the tendency to reduce the efficiency of energy conversion as a result of several power processing stages. It should be noted also that the inverter cannot be operated in parallel with the diesel generator therefore it must be sized to supply the peak load. Its failure will result in power interruption if the load cannot be supplied directly from the diesel generator in emergency situations

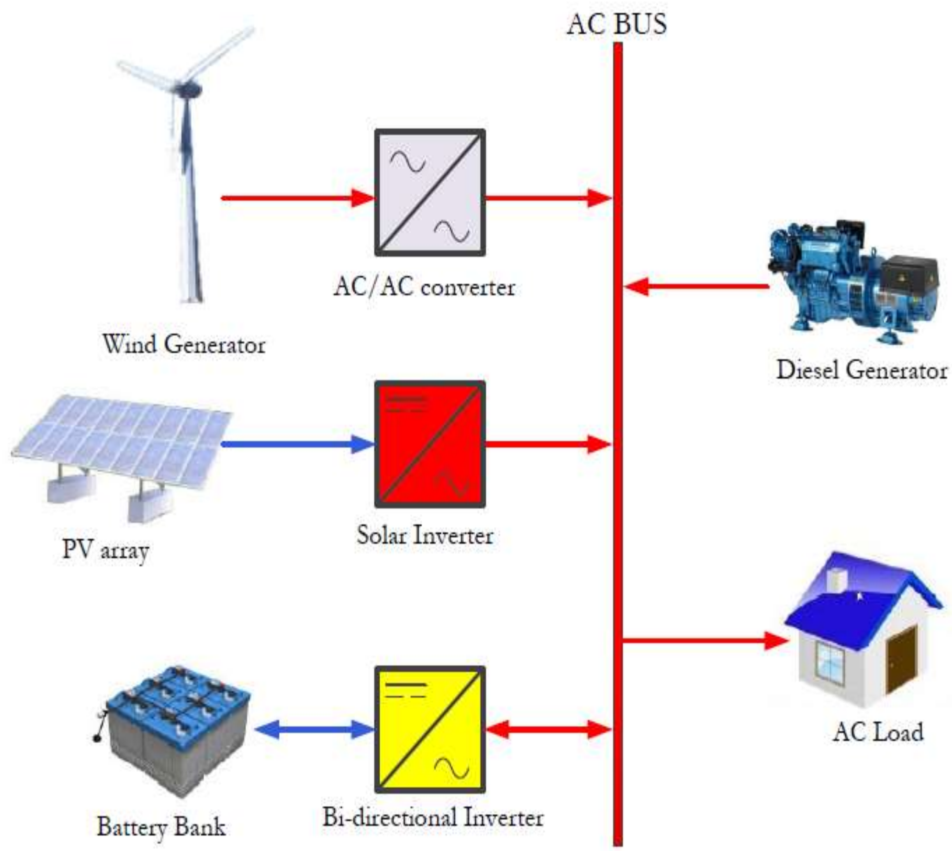
*Figure 21: Illustration of a DC coupled hybrid system*




Source: (Ranaweera, June 2013)

**AC coupled Hybrid system:** In this configuration, all electricity generating systems are connected to the AC bus. The DC generating systems are connected to the AC bus via inverters and AC generating components can be directly connected to the AC bus or may need an AC/AC converter to enable stable coupling. The energy supply for the battery bank is controlled by a bidirectional inverter in this system. This system is easy to connect to the grid (because most national grids and the Nigerian national grid is AC coupled) if the grid extends to the remote area in the future. AC coupled hybrid configurations are highly recommended for hybrid systems design and implementation. See the schematic for AC coupled hybrid system in figure 22.

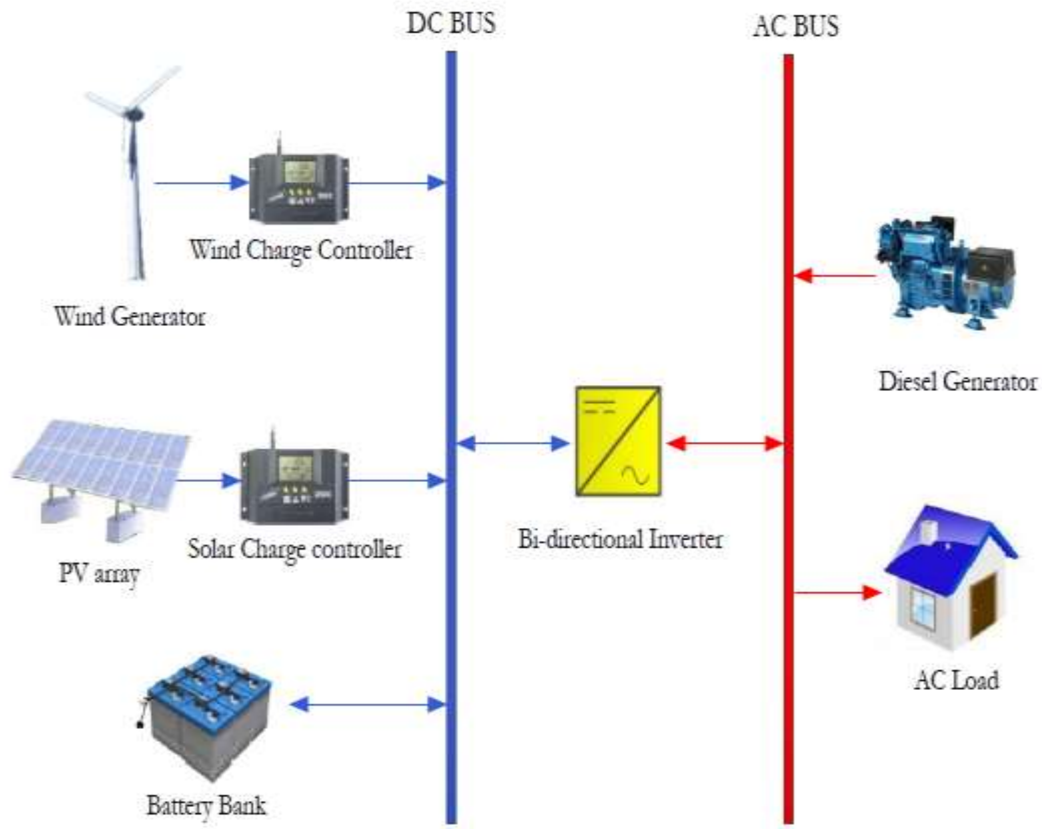
*Figure 22: Illustration of a AC coupled hybrid system*




Source: (Ranaweera, June 2013)

**DC/AC coupled hybrid system:** This configuration make use of both Power frequency AC coupled and DC bus to integrate all the energy sources whereby DC power source are coupled to DC bus, DC loads served from DC bus through a DC/DC converter using the right interfacing circuits. Figure 23 illustrates DC/AC Coupled hybrid system.

*Figure 23: Illustration of a DC/AC coupled hybrid system*

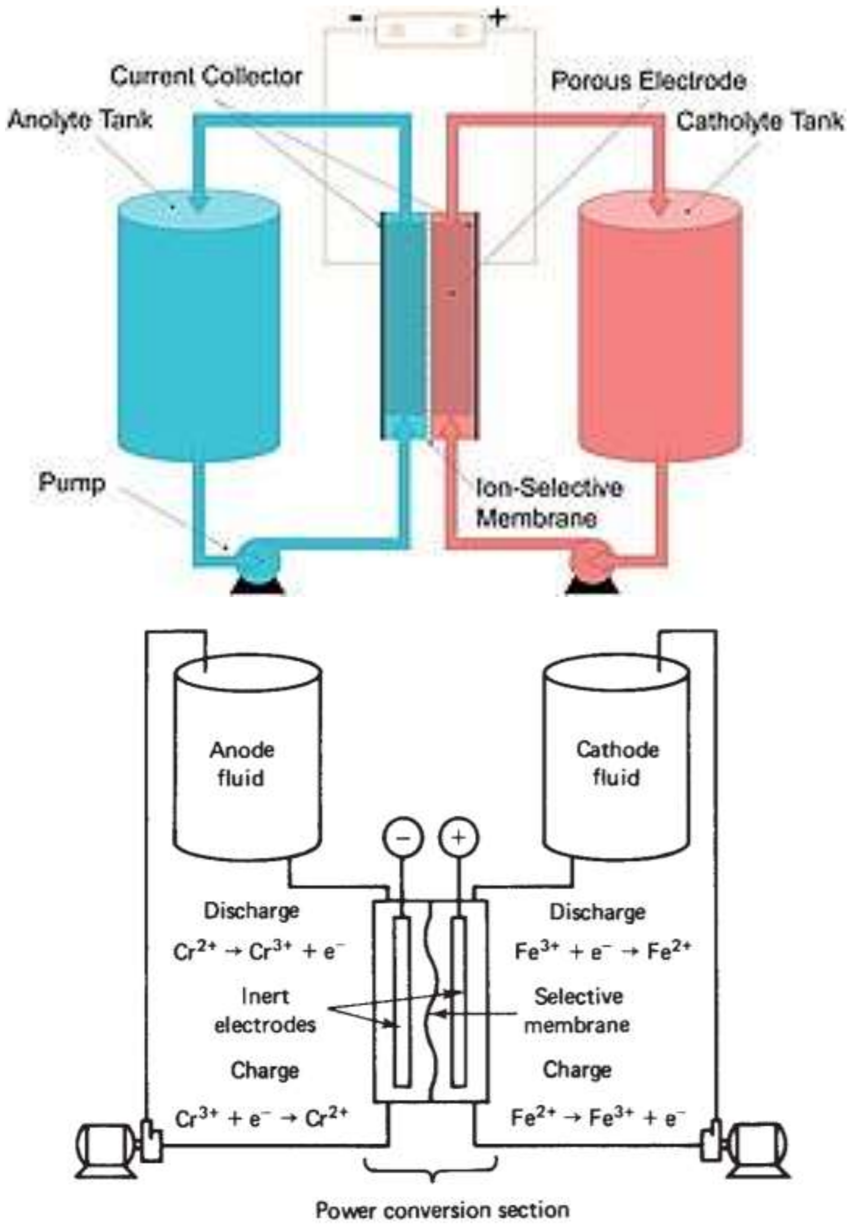



Source: (Ranaweera, June 2013)

## 2.10 Energy Storage

In many cases, electrochemical batteries have been the predominant choice for the storage of photovoltaic system and various innovations, through research has been achieved with new modern batteries; which has now found uses in cars, electrification and space sciences. Lead-Acid and Nickel-Cadmium (Ni-Cd) batteries have been mostly used in this regards and more for new materials that will Lead to a higher power density, environmental and high life cycle for the battery cells. An example of a high life cycle battery is the Zinc-Chlorine (Zn-Cl) battery cells and also for high temperature applications is the Sodium-Sulfide (Na-S). The Redox flow batteries as show in figure 24 below is a good recommendation for solar PV applications especially in standalone applications even though the cells have a low power density (Martin A. Green, 1982). The fact that the battery cells has a long life cycle of up to 30 years is a huge benefit added with the relative cost effectiveness makes it an ideal choice for standalone solar PV systems.

*Figure 24: Schematic diagram of an electrically rechargeable redox energy storage system*




Source: Wikipedia, 2019; Solar Cells by Martin A. Green, 1982

Even though batteries are suitable for storing energy for small scale applications, when it comes to very large scale applications, the use of batteries tends to become less cost effective. In these type of applications, the Pumped Hydro Energy Storage is recommended. This is done by pumping large volume of water from a reservoir up to a hill of know height during the period of low energy demand. The energy can be generated back, up to 2/3 of the required energy to pump the water uphill can be recreated, by allowing water to flow in the opposite direction to drive the turbines, generating power in the process. The challenge with this type of storage even though effective, is the availability of suitable sites. This can be mitigated by creating huge depth in chose site location and then pumping water from the underground to a certain height, to store the excess energy. We can also use excess energy to store compressed air in an underground reservoir. The air is then released to turn a turbine which in turn is used to generate electricity or other forms of energy. This approach, has an advantage of a higher energy density and also with the flexibility of siting the ground reservoir than the water storage option. Because of compressed air high energy output, such systems can be built in a small size which results to a much cost effective storage option for the entire system.

Energy storage can also be achieved by the conversion of hydrogen. This approach is reported to be very suitable with the use of PV because of the low-voltage dc requirements of electrolysis through a process widely known as Photoelectrolysis. Also, Hydrogen can be transferred to a very long distance and this feature gives it a lot of advantage for application in various areas, such as conventional engines for motive power or in fuel cells for electricity generation. Because of its diverse applicability, the concept of a Hydrogen Economy has been proposed by some researchers like, where hydrogen forms the basic fuel for mankind, and our entire economy can be built around it. The hydrogen economy is proposed as part of the future low-carbon economy, towards phasing out fossil fuels and limiting global warming. The combustion of hydrogen only releases clean water, and no $CO_2$ to the atmosphere, this makes it ideal for the fight against climate change. Based on the information on Wikipedia (2019), hydrogen is mainly used as an industrial feedstock, mostly for the production of ammonia, methanol and petroleum refining. More research has led to new materials which can leverage the diverse applicability of Hydrogen but with better efficiency. Alternatives such as superconducting magnets and metal hydrides has been proposed as promising substitutes with better efficiencies. Despite the progress that has been made in research so far, one of the major factors that are considered in energy storage and also mini-grid system design is cost required for the system development. Because of the cost benefit that comes with the use of Lead-Acid batteries and its relative good cycle life and efficiencies, it’s still the most widely used battery cells. For this work, we will also be making use of lead-acid batteries for our system design.

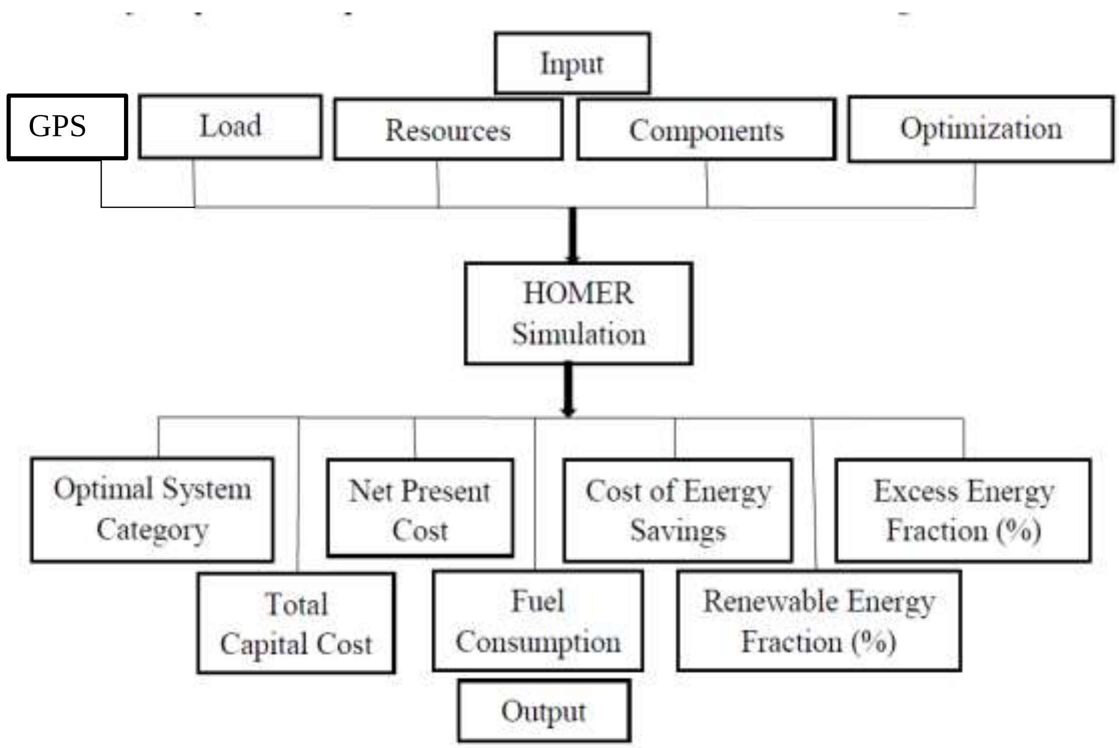
### 2.11 HOMER Energy Simulation Model

HOMER is an acronym which stands for Hybrid Optimization of Multiple Energy Resources. It is a powerful computer software modelling tool for designing, simulating, and analysing standalone and grid-connected power systems containing many combinations of conventional generators, wind turbines, PV arrays, hydropower power generation, biomass power plant, micro-turbines, hydrogen storage, batteries, combined heat and power, fuel cells, boilers, electrolysers, AC/DC bi-directional converters and others, to serve both thermal and electric loads (Asrari, A. et al, 2012). HOMER can simulate and optimizes an electric power system combining traditional and renewable generation sources. HOMERS has great features which helps it to stand out among other modelling tools; with its chronological detailing, short simulation time, transparent methodology, and accessible interface are unique. HOMER performs detailed chronological simulations at an hourly (or even minute-by-minute) level. Using site-specific information about loads, resources, technology costs and performance, HOMER simulates all possible permutations of the system and then ranks the results, clearly showing the optimal, least-cost configuration and both the initial investment cost and the payback time. In addition, it is capable of carrying out sensitivity analyses to demonstrate the results of uncertainty in any of the input parameters.

### 2.11.1 HOMER Input Data

Analysis in HOMER requires input data such as energy resource data of the site, load data, components types and installations (including size, costs, lifetime, replacement costs, maintenance costs, operation costs etc.), expected lifetime of the entire project, inflation rate, discount rate, fuel cost, efficiency rate, etc. Figure 25 below gives a brief summary of the fundamental input data required for the HOMER software to operate optimally.

*Figure 25: HOMER input-output parameters*



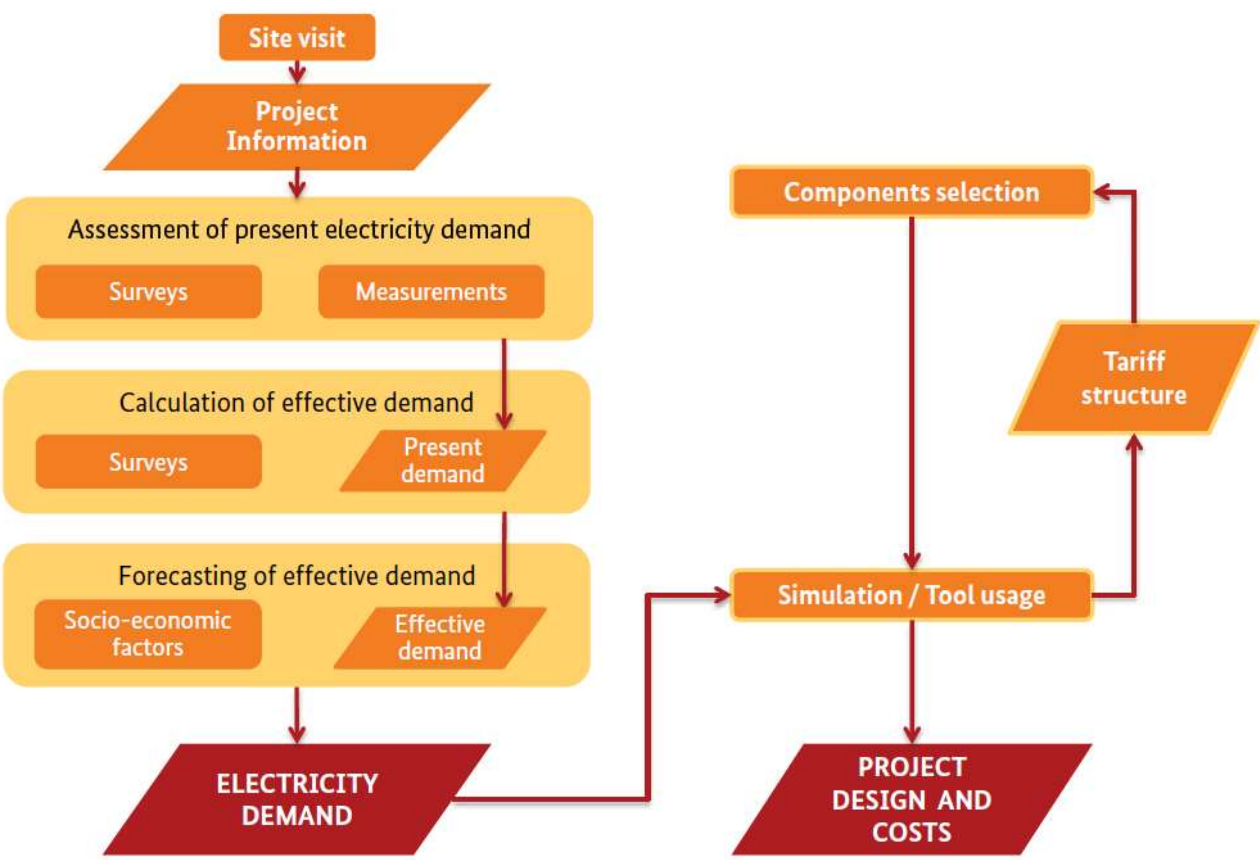
## Chapter Three

# 3.0 Research Methodology and Data Collection

## 3.1 Mini-grid Sizing Guidelines and Standard

In the sizing process of a mini-grid, several factors and data need to be assessed before proceeding to the size selection of the components and the financial evaluation. It has to be highlighted that every case study location differs in terms of needs and conditions. Hence, there is not one standardized methodology that can be applied, but recommendations that can be used and adapted to specific cases. The steps during the sizing process can be split into the demand assessment and forecast on the one side and the technical and financial analysis on the other. The research design which described steps and actions to be taken is show in the flow chart in Figure 26. The demand assessment is the most critical step in the system sizing process of a mini-grid for the case study location for this research. The results of the assessment have the highest impact on specifying the system size of the system and therefore was given all necessary attention in other to avoid system under-sizing or oversizing. See Appendix 2 for details of the questionnaire sample for the survey.

*Figure 26: Flow chart of the sizing process (Research Design)*

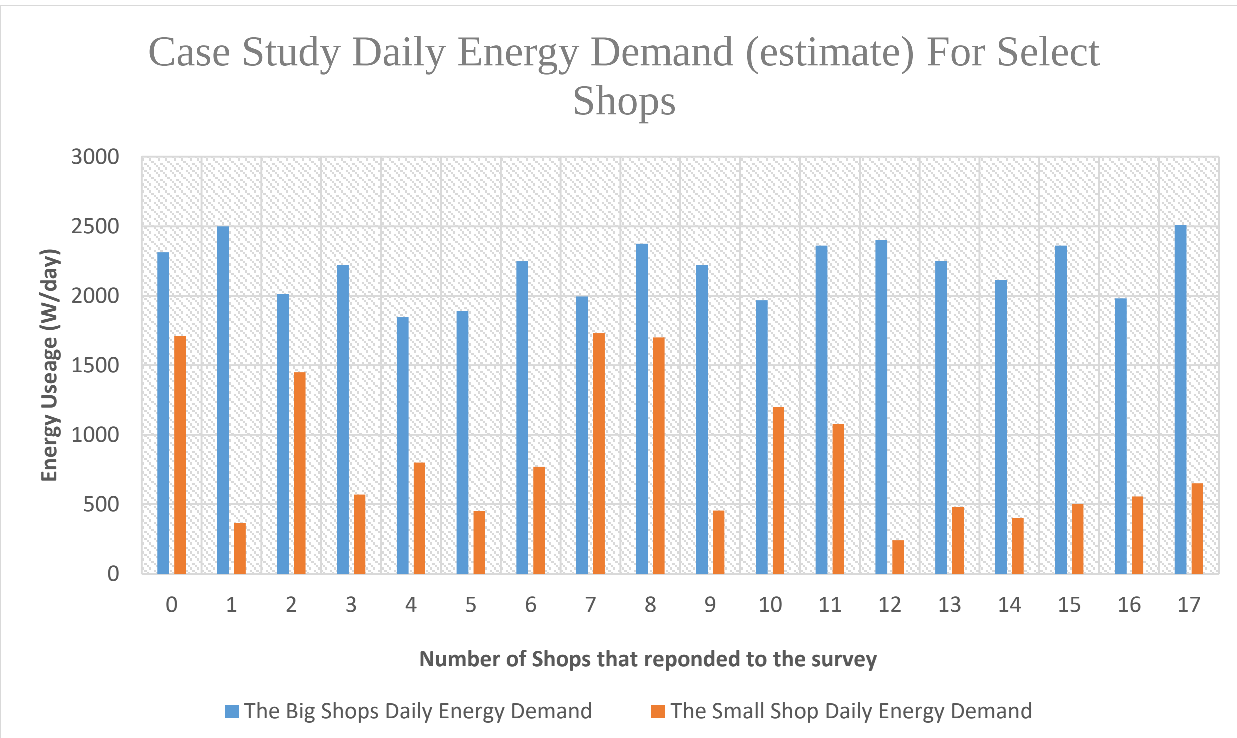



Source: GIZ, Mini-grid sizing

### 3.1.1 Case Study Location Demand Assessment

The recommended approach for energy demand assessment of case study location is to organize a community-wide meeting and in the meeting, clearly and carefully present the electricity use options and constraints that will be imposed on end-uses by the supply and estimated cost of electricity. This is then followed by a survey of potential energy consumers; about their initial level of expected demand, a realistic projection of growth, and the type of service (i.e., whether and where three-phase distribution is necessary) assuming the consumers are heavy consumer like business units and manufacturing industry. Based on the production and consumption patterns estimated, an initial tariff can be reached. A critical step in the initial planning process is to estimate the maximum initial peak load that the prospective consumers are to impose on the system and how this load is expected to grow over time.

*Figure 27: Estimated daily energy load demand profile for select shops in case study location*




Source: field data collected

The end-product of the demand assessment is a load curve in kW over time. This load profile is roughly steady once the business hours resumes from 8am until 6pm for six days a week as show in figure 27 above. The tool that has been used for this research is the HOMER Pro mini-grid System simulation software. By following the system sizing standard that has been developed by the GIZ, the Effective electricity demand of the peak value of 135kW at a consumption rate of an average of 1055kWh per day was calculated for the case location. From figure 27 above it is seen that because most of the shops in the plaza engage in similar computer accessories businesses, their energy demand profiles follow similar pattern and on an average is at 2197.7W per day for the big shops and 839w per day for the small shops. This gives a rough total peak demand of about

208kW per day in the case study location for an estimated 200 shops in the site. Currently, Binitie plaza generates its own electricity by means of a generator with an output of 100kVA which is approximately 80kW peak supply from the generator. Base on feedback from the site visit, it was seen that the load demand of the plaza is slightly higher than what the generator can provide and even estimated peak demand is 208kW for 200 shops (it is important to note that the number of shops might be less), the simulation of the HOMER was carried out with an estimated peak of 135kW and an average consumption of 1055kWh per day. This was done in other to avoid the case of oversizing of the system and also to avoid the development of a system that the shop owners cannot afford to pay for.

The consumption load of the energy consumer is the sum of the loads actually on at any instant of time. This is generally different from the sum of all the individual community loads because all these loads are not generally on at the same time, i.e., they do not coincide. The best way to establish consumers' energy consumption is with meters. Metering is done through the use of an energy or kilowatt-hour meter. This is regarded as a more equitable approach, because a consumer is charged according to the energy actually consumed. Those who use less electricity pay less. This study determined consumption by taking an inventory of the various shops load equipment in the Plaza and multiplying by the estimated hours that they all operate within the day.

### 3.1.2 Demand-side management of the case location

One of the main objectives of this research is the incorporation of a demand-side management implementation approach. Which in essence means that this work aims to find out approaches that will involving the case business location towards making the solar PV system alternative efficient and cost effective. Once the consumption demand has been properly estimated and the required data for the system feasibility simulations in HOMER pro are ready. This research work also made sure to collect data that will help determine the consumption behavior of the shop owners, their level of education, age and also if they have been practicing any form of energy efficiency in the past. These collected data are aimed towards further reducing the project cost by either reducing or completely eliminating the operation and maintenance cost for the PV system and the generator. Demand-side management can also be achieved by managing the consumption pattern of the shop owners in order to achieve more efficient use of the power supply and eventually cut down on daily consumption. The Demand-side management approach of this research attempt to incorporate the shop owners in the maintenance routine of the system and the education level of the shop owners and employees was used to determine the shop owners that will be trained during the system development stage to eventually be used in the management and the maintenance of the mini-grid system.

### 3.1.3 Willingness and Ability to Pay (WTP and ATP)

Based on the feedback from this research survey tools (using an improved GIZ mini-grid sizing questionnaire template), it is seen that 100% of the business owners are eager to get access to electricity with an alternative which is affordable; however, this is clearly not a sufficient condition for embarking on the implementation of a mini-grid project. It is important to determine if the customers have the ability to pay and is also willing to pay for the service. WTP is "the maximum amount that an individual or a shop owner indicates that he or she is willing to pay for a good or service" (NRECA, 2009). WTP varies from the energy customer to the other and in this case the energy will be used for productive consumption. This work made use of a direct survey in other to determine the shop owners' willingness and ability to pay by collecting information on the revenue generation per week and also on the amount of money they pay their employees and the current cost of their electricity and also the cost for rental per month. Knowledge about ATP allows for better determination of the appropriate size of the system, and also for setting the electricity tariffs in better proportion to the customers' needs and financial capacity.

*Table 4: Data on the case location willingness and ability to pay*

| **Willingness to pay** | | | |
|---|---|---|---|
| What is important to you | Cost of electricity = 100% | | Duration of supply = 83% |
| What most likely will drive you to connect | Neighbors connected = 15% | Own need for electricity = 33% | Low connection fee = 100% |
| Will an electricity mini-grid improve your life or business somehow | Yes = 100% | | |
| On which base do you think the provision of electricity should be ? | | Commercial = 27% | On an end user micro financed model = 83% |
| Who decides for the business to pay for electricity | | My Boss = 25% | The Plaza = 75% |
| Does the business already have an individual solar system | | No = 80% | Under consideration (currently using battery) = 20% |
| How happy are you with your current electricity supply | | Not very happy = 83% | Can live with it 28% |

Through the survey – results shown in table 4 and 5, this research was able to find out that the business owners collectively pay seven hundred thousand naira (700,000 naira) monthly for the fueling and serving of their generator. 67% of the respondent said that they will be willing to pay more for an alternative that is sustainable and stable even though they are already paying too much for electricity. One of the goals of this research is to investigate the feasibility of a cost effective alternative which incorporates Solar PV in the energy production system. From the average revenue data collected from the shop owners and by deducting expenses like rent, employees' salaries from the revenue. The average net revenue value gives an indication what the shop owners might be willing to pay for the cost of electricity. Also, the chairman of the plaza gave his assurance that he believes that the only real sell for an alternative electricity supply; as seen from the data is the cost of the electricity (with 100% of the respondents stating that the will first consider the cost of the energy before any other criteria) and that he can only recommend the feasible system to his colleagues, if the system can give them a rate that is cheaper than the 700,000 naira they currently pay monthly for the servicing and maintenance of their genset. Based on his feedback, these research work based the feasible LCOE as that which is less than 700,000 naira per month and also will be able to ensure that the CAPEX of the system is recovered at least within the first 10 years of the mini-grid system's life time.

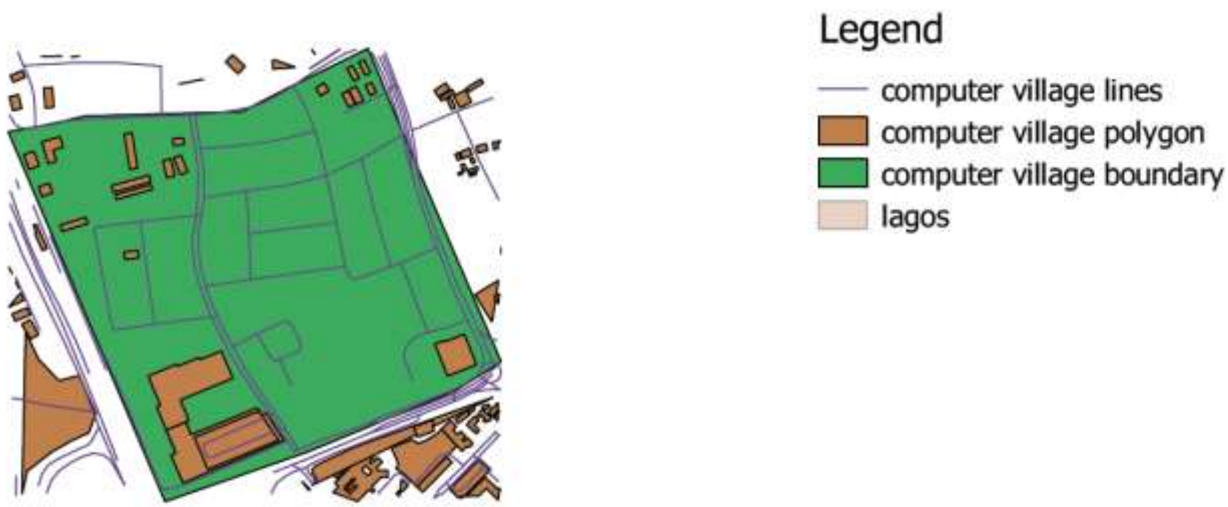
*Table 5: Mini-grid sizing field data collection*

| Average age of shop owners and employees = 32 | Average revenue per week (naira) - Big shops (Average = 150,278) | big shop estimated daily load demand for selected shops (Watts) Aerage = 2197.7W | small shop estimated daily load demand for selected shops (Watts) Aerage = 839W | Average revenue per week (naira) Average = 69,706 | Current shared cost of electricity per month = 700,000 (naira) | Percentage of total Secondary school level educated business owners and employees | Business with standby sources of electricity | Business Practicing any form of energy efficency measure |
|---|---|---|---|---|---|---|---|---|
| 30 | 240,000 | 2312 | 1710 | 125,000 | Big shops = 4,500 | 63% | Yes | Yes |
| 35 | 200,000 | 2500 | 364.3 | 150,000 | Small shops = 3000 | | Yes | Yes |
| 40 | 150,000 | 2010 | 1450 | 70,000 | | | Yes | Yes |
| 27 | 130,000 | 2223.4 | 570 | 80,000 | Cost for yearly rent for the shops | Businesses with over 5 employees (inclunding apprentice) | Yes | Yes |
| 26 | 125,000 | 1845 | 800 | 100,00 | | | Yes | Yes |
| 27 | 100,000 | 1889 | 450 | 60,000 | Big Shops = 800,000 - 1M | 87% | Yes | Yes |
| 30 | 180,000 | 2247 | 770 | 55,000 | small shops = 200,000 - 400,000 | | Yes | Yes |
| 28 | 175,000 | 1994 | 1730 | 70,000 | | | Yes | Yes |
| 33 | 125,000 | 2375 | 1700 | 40,000 | Businesses that are affected by power outage negatively | | Yes | Yes |
| 35 | 100,000 | 2221 | 455 | 50,000 | 100% of respondent | | Yes | Yes |
| 38 | 90,000 | 1967 | 1200 | 100,000 | | | Yes | Yes |
| 29 | 110,000 | 2360 | 1079 | 60,000 | Business Identified Issues with Power Utility | | Yes | Yes |
| 30 | 80,000 | 2400 | 239.8 | 55,000 | Black outs | | Yes | Yes |
| 31 | 80,000 | 2250 | 480 | 70,000 | Unannounced power outages | | Yes | Yes |
| 27 | 200,000 | 2115 | 400 | 80,000 | High tariff | | Yes | Yes |
| 36 | 240,000 | 2360 | 500 | 50,000 | | | Yes | Yes |
| 28 | 230,000 | 1980 | 555 | 40,000 | Businesses that willing to pay more for an improved service or alternative | | Yes + Battery | Yes |
| 30 | 150,000 | 2511 | 650 | 30,000 | 67% | | Yes | Yes |

Source: Field data collection

### 3.2 Description of the site – Binitie Plaza (Computer Village, Lagos Nigeria)

*Figure 28: Open Street Map of Computer Village Lagos*



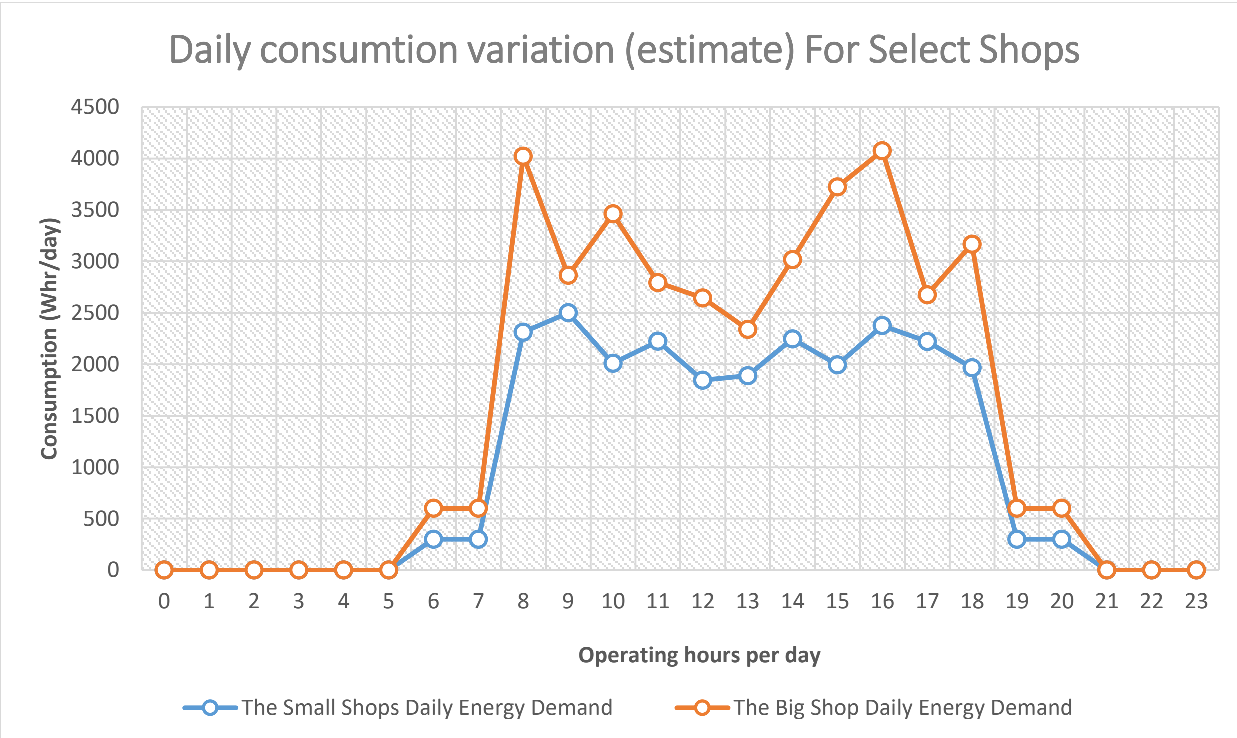

Source: Open Street Map Data

Computer village business district is located in Ikeja local government council, Lagos Nigeria on the Latitude of $\mathbf{6.5968°}\ \boldsymbol{N}$ and Longitude $\mathbf{3.3408°}\ \boldsymbol{E}$. the business district is a major business hub in Lagos and most businesses in this location deals on the buying, selling and repairs of computer accessories. The location's energy consumption level is relatively constant but in many cases not considered as a heavy energy user location. This is because the MSMEs in this location mostly use low power electronics for their activities. A particular cluster of shops within computer village was used as a case study for this research. The plaza unit comprises of an estimated 200 small businesses which are completely not connected to the grid for their energy supply but rather collectively power the plaza with a generator of 100kVA output. While collecting the data for this research, it was discovered that the current output of the gen is insufficient for the energy demand of the plaza. The rooftop area estimated measurement of the Plaza using QGIS gave an estimate of 13,407.35m$^2$ – this means that the case location has sufficient rooftop area for a solar PV power output of about 11,369.24kWp assuming a solar cell efficiency equal to 17.89% and a derating factor of 1 (zero capacity factor).

The chairman of the plaza gave a breakdown of how the energy of the plaza has been managed for the past four years. He confirmed that it cost the shop owners collectively, 700,000 Naira monthly for both the fuelling and servicing of the generator for the plaza. He further stated that his fellow business owners are very much willing to switch to a more cost effective energy source such as solar PV mini-grid. Figure 28 shows the open street map view of the case study location and the polygons on the image is the normal sizes of the various plazas within the business district. Using QGIS software, it was possible to estimate the average rooftop area of the Binitie Plaza. The estimated rooftop area is sufficient for the require solar PV output for the optimal system implementation and even for future expansion plans.

### 3.2.1 Estimated Consumption Profile of Binitie Plaza SMEs

*Figure 29: Daily consumption profile estimate for select shops*




Source: Field data collection

The methodology used in gathering this consumption profile has been explained in the previous section of this chapter. The load data took over two weeks to gather, and required that a meeting is convened with the shop owners including the plaza chairman and the landlord of the plaza. From figure 29 above, it is seen that even though the big shops consume more electricity per hour when compared to the small shops, they both relatively maintain similar consumption pattern. One of the assumptions for this research is that the rest of the shops in the case study location has similar consumption profile such as seen in figure 29 above. The total daily consumption estimate for the whole plaza was capped at a peak value of 1055kWhr per day. This peak value was then used for the simulation of a feasible system using the HOMER Pro software. This research also led to the creation of a documentary video which recording some of the activities during the data collection process.

### 3.2.2 Solar Resources of the case study location

As discussed in chapter two, Nigeria has a relatively high insolation rates, with an average of 5-7 peak sunshine hours and average daily insolation of 4-5.7 kWh/m$^2$. Electricity generation potential in Nigeria from solar PV is far greater than what is consumed yearly from the national grid if properly harnessed. Due to the unavailability of ground measurement data of solar radiation at the selected location, data have been obtained from the NASA renewable energy resource website.

Daily average insolation data on a horizontal surface obtained from the NASA database are plotted (for a year) in HOMER for the case study location as shown in Figure 30. Also, figure 30 contains a tabular monthly averaged insolation incident on a horizontal surface and the clearness index. The clearness index is a measure of the clearness of the atmosphere. It is the fraction of the solar radiation that is transmitted through the atmosphere to strike the surface of the Earth. It is a dimensionless number between 0 and 1, defined as the surface radiation divided by the extra-terrestrial radiation. The clearness index has a high value under clear, sunny conditions, and a low value under cloudy conditions. The clearness index can be defined on an instantaneous, hourly, or monthly basis. The clearness index values in HOMER's Solar Resource inputs window are monthly average values. The symbol for the monthly average clearness index is $K_t$. Typical values of $K_t$ range from 0.25 (a very cloudy month, such as an average December in London) to 0.75 (a very sunny month, such as an average June in Phoenix) (HOMER Energy Resource Explanatory online publication).

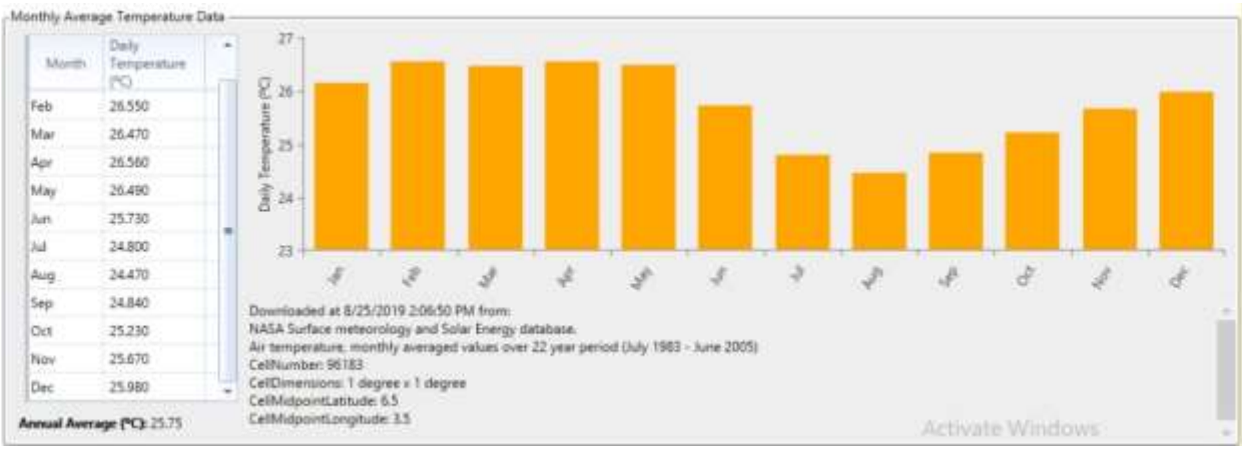
*Figure 30: Daily average insolation incidents on a horizontal surface and clearance index throughout a year for case study location*


Source: HOMER Software

### 3.2.3 Temperature Profile at the Site

The temperature of the site plays an important role in power generation because it impacts the efficiency of the solar cell. The higher the environmental temperature the less the efficiency of the solar cells. For this work, a temperature sensitivity variation for the HOMER simulation was set for different temperature variations: 20, 30, 25.745 degree centigrade. In the simulations, very little to no changes in the outcome of the HOMER results was found based on temperature variation; therefore, this report did not consider the effect of temperature on the feasibility of the system in the analysis. This does not mean that the effect of temperature is not there. It is possible that the range of sensitivity variation that was chosen for this research simply was not significant enough to lead to a significant change in the HOMER simulation output. At the Binitie Plaza location in Ikeja, Lagos, Nigeria, NASA data shows that February has the highest temperature with approximately 26.550$^{0}$C while August has the lowest temperature of approximately 24.440$^{0}$C.

*Figure 31: The average monthly temperature variation of the site*




Source: HOMER Software

### 3.3 Hybrid System – Components, Characteristics and Costs

The hybrid system considered in this study consist of the following components: PV module, diesel generator, battery, and bidirectional converters. The components of each system was chosen based on the system composition and configuration. The cost information of solar PV module, diesel generator, inverter and battery are obtained from local suppliers (when possible) and where absent, the manufacturers and foreign retailers' prices was used. A detailed specifications and price estimations of these components are shown below. All the systems considered in this study have different lifespan based on manufacturer's specification and the project life is taken as 25 years.

#### 3.3.1 Photovoltaic Panels

The physical examination of the site shows that the PV panels can be installed on the roof tops of the buildings on a fixed axis, at an angle equivalent to the latitude of the site for optimum solar radiation capturing. Factors including the size of panel, types, the brand manufacturer, the retailer and country in particular affect the cost of PV modules. In this research, the CS3U-355P-40MM Canadian Solar was selected for the HOMER simulation with the characteristics given in the table below and panels with equivalent characteristics are available in the Nigeria markets. The cost of each panel plus installation charges per panel equal 37,000 Naira. "The PV derating factor is a scaling factor that HOMER applies to the PV array power output to account for reduced output in real-world operating conditions compared to the conditions under which the PV panel was rated" (HOMER help manual). It compensates for reduction in efficiency of PV modules arising from temperature increases, dust accumulation and wiring energy losses is taken to be 0.8 (PV derating factor typically ranges from 0.7-0.8 for high temperatures) (HOMER Energy Help book). The ground reflectance (fraction of incident solar radiation on the ground that is reflected back to space) ranges from 20-70% depending on the ground nature at the location of study. In this study, ground reflectance is assumed to be the minimum (20%). This PV module will be mounted on a fixed axis oriented at an angle above the ground equivalent to the latitude at the site and facing south with an azimuth angle of zero. There will be no tracking of the sun due to cost constraints.

*Table 6: Characteristics of Selected PV Panel*

| **Characteristics of Selected PV Panel** | |
|---|---|
| Item code | Canadian Solar, Inc. |
| Model Number (STC) | CS3U-355P-40MM |
| Nominal Max Power ($P_{max}$) | 300 watts |
| Optimum Operating Voltage ($V_{mp}$) | 39.4V |
| Optimum Operating Current ($I_{mp}$) | 9.02A |
| Open Circuit Voltage ($V_{oc}$) | 46.8V |
| Short Circuit Current ($I_{sc}$) | 9.59A |
| Module Efficiency | 17.89% |
| Maximum System Voltage | 1500V (IEC/UL) |
| Maximum Series Fuse Rating | 30A |
| Cell Type | Poly-crystalline<br>Split Cell |
| Cell Arrangement | 144 [2x (12 x 6)] |
| Operating Temperature | -40°C ~ +85°C |
| Frame | Silver Aluminium<br>w/Back Crossbar |
| Snow/Wind Loads | 5400 Pa/3600 Pa |
| Dimensions | 78.7 x 39.1 x 1.57in<br>(2000 x 992 x 40mm) |
| Weight | 49.6 lbs (22.5 kg) |
| Connectors/Cables<br>Life time | T4/12 AWG Cables<br>25 years |

### 3.3.2 Diesel Generator

Diesel Generators are an important component in hybrid renewable energy systems. They help to play a system stability and backup role, towards improving the quality and availability of power supply. The Generators are of significant importance especially during periods when there is low power output from other energy generators in the hybrid system so as to ensure system reliability and effectiveness in meeting full load demand. To model a diesel generator for maximum power production for the hybrid system, the diesel price is taken into consideration. At present, the diesel price in Nigeria is 160 Naira ($ 0.44). Since the site is located in urban centre, transportation cost is not included. The research also included sensitivity cases since the cost of fuel is not constant (150, 160, 170). The size and capacity of a commercially available diesel generator is proportional to its cost. It is also worthy of note that a generator set is already in place in this case study site and is currently the main sources of electricity generation (Base System), currently generating an insufficient peak of 80kWp. This research work considers the generator as a backup. It chose a generator capacity of 100kWp for the HOMER simulation. This capacity can be found within the Nigeria market and can be purchased at a cost of 8.4 million Naira for the *Mikano brand*. The replacement cost for this generator was assumed to be equal to its initial purchased cost and a lifespan of 12.5 years was assigned to the generator in the simulation. Some of the simulations was also ran assuming a zero initial capital cost for the generator.

### 3.3.3 Battery Selection and Cost

In this study, the Surrette 6CS-25PS battery was selected for the system simulation. The battery cost $1,100 each. The total capital cost including the shipment and installation cost is $1,200 per one. Its characteristics are given in table 7 below. The lifetime of the battery is given by the manufacturer to be 15 years. In terms of quantity required to meet the maximum load, the optimization option was chosen so that HOMER will make that decision after the simulation.

*Table 7: Characteristics of Selected Battery*

| | |
|---|---|
| Capacity | 840Ah |
| Nominal Voltage | 6V |
| Nominal capacity | 6.91kWh |
| Maximum Capacity | 1156Ah |
| Minimum State of charge | 40% |
| Maximum discharge current | 41A |
| Round trip efficiency | 80% |
| Capacity Ratio | 0.237 |

### 3.3.4 Converters Selection and Cost

Any system that contains both AC and DC elements requires a converter. Inverters (converters) maintain the flow of a single form of current into the load system by converting all current types from the different energy generators into a single current form that is required as output current. Hybrid system can consist of both the AC and DC system that require an inverter or converter to convert the DC voltage from the batteries to AC voltage required by the load or to convert the AC current from the generator to charge the battery. When power generated from the renewable sources is small, the generator will do the work of charging the batteries. There are usually grid-tied inverters and off-grid inverters but due to advancement in technology, these two are now incorporated in one in the case where both are required. For this work, only bidirectional converters were used for the system simulations and it was chosen because it can do the work of both an inverter and a rectifier. The rated power of the inverter should be equal to or larger than the peak load but since the load will supply both from the renewable and non-renewable, below the peak can be installed. The operation and maintenance cost for this component was rated at zero for we assumed that the shop owners will be train on how to replace the batteries themselves the only additional cost considered was the replacement cost.

Converter sizes considered are: 0, 100, 150 and 200kW in the HOMER simulation search space option. Capital cost of converter including importation cost and installation cost was inputted as $4,500 per 8kW and the replacement cost is about $4,000. The efficiency of converter is 95% and the lifetime of the converter was given by the manufacturer at 15 years.

### 3.3.5 Controller options

The Controller component allows specification of how HOMER system operates during the simulation. Each controller uses a unique control algorithm or dispatch strategy. If you add multiple Controller components to your model, HOMER simulates and optimizes the system with each Controller, and presents the results so you can compare the performance with each control algorithm. For this work, we set the controller option at optimize – so that HOMER will make the decision for the output.

### 3.3.6 Dispatch strategy

A dispatch strategy is the system optimized rule that is set for the control of the generator and the batteries operation in a hybrid system (HOMER help hand book). In this study, the only dispatchable energy source used is the diesel generator. Power from the renewable energy sources are used, when it is available – to supply the load or to charge the battery bank. When the power generated from the renewable energy sources is low, the generator does the work of charging the batteries. Sometimes, operating the generator at its full capacity when required and using the excess energy to charge the battery bank may be more economical than the previous case. HOMER uses two dispatch strategies:

- Cycle Charging (CC): The cycle charging strategy is used to automatically turn on the generator whenever needed to supply electricity and also charges the battery. Cycle charging is mostly recommended when the systems has little or no renewable energy source like solar or wind. It is abbreviated "CC" in the table in Appendix 3.
- Load Following (LF): In this strategy, when a generator is needed, it produces only enough power to meet the demand. Load following tends to be optimal in systems with a lot of renewable power that sometimes exceeds the load. It is abbreviated "LF" in the Appendix

3 tables of full simulation Results page. In this study, the dispatch strategy was set at optimize.

The choice for a dispatch option was set to optimize such that HOMER determines the most suitable dispatch strategy for the various simulation options.

## 3.4 Economic Criteria for system simulations and selection

### 3.4.1 The total Net Present Cost (NPC)

This is the cost of a system in the present value of all the costs the system incurs over its lifetime, minus the present value of all the revenue it earns over its lifetime. Costs include capital costs, replacement costs, O&M costs, fuel costs, emissions penalties, and the costs of buying power from the grid. Revenues include salvage value and grid sales revenue. HOMER calculates the total NPC by summing the total discounted cash flows in each year of the project lifetime. The total NPC is HOMER's main economic output, the value by which it ranks all system configurations in the optimization results, and the basis from which it calculates the total annualized cost and the Levelized Cost of Energy (LCOE). The present value of the costs that will make *n*-year later can be calculated by the following formula.

$$C_{NPC} = C\left[\frac{1+i'}{1+d}\right]^{n} \tag{3}$$

Where:

$d$ is the nominal interest rate (%)
$i'$ is the annual inflation rate (%)

To determine the LCOE, the total NPC of the project must be converted to series of equal annual cash flows which is known as total annualized cost. The following equation is used to calculate the total annualized cost:

$$\text{Total annualized cost (\$/year)} = \text{Total NPC x CPF} \tag{4}$$

Where, CPF is the capital recovery factor which is a ratio used to calculate the present value of an annuity (a series of equal annual cash flows). The equation for the capital recovery factor is given by the formula:

$$Capital\ Recovery\ Factor = \frac{i(1+i)^{N}}{(1+i)^{N}-1} \tag{5}$$

$N$ is the number of years
$i$ is the real interest rate (i.e. the discount rate used to convert between one-time costs and annualized costs).

$N$ is equal to 25 years in this study. The real discount rate is used to convert between one-time costs and annualized costs. HOMER calculates the annual real discount rate (also called the real interest rate or interest rate) from the "Nominal discount rate" and "Expected inflation rate" inputs. It uses the real discount rate to calculate discount factors and annualized costs from net present costs. The real discount rate is given by the formula:

$$i = \frac{d-i'}{1+i'} \quad (6)$$

The discount factor is a ratio used to calculate the present value of a cash flow that occurs in any year of the project lifetime. HOMER calculates the discount factor using the following equation:

$$f_d = \frac{1}{(1+i)^N} \quad (7)$$

Where:

$i$ = real discount rate (%)

$N$ = number of years

Nigerians inflation rate fluctuates. As at November 2018, it was at 12.09% for 2019, it has been project to be around 11.37%. Therefore, an inflation rate of 12% had been used in this simulation. The discount rate is kept constant at 13% by the CBN. The normal interest rate in Nigeria from banks to businesses is in double digits and sometimes even up 20%. For this work, 18% interest rate was used.

### 3.4.2 Annualised system cost (ASC)

ACS is the sum of the annualised cost (capital, replacement and maintenance) of all the system components.

$$ASC = Annualised\ (capital + replacement + maintenance)costs \quad (8)$$

### 3.4.3 Levelized cost of Energy (LCOE)

LCOE evaluates the system taking into account all recurring and non-recurring costs throughout the lifespan of the project. It is the ratio of the total annualised system cost (ASC) to the annual electricity production (Total) in kWh. Mathematically:

$$LCOE = \frac{Total\ Annualised\ cost\ (USD/yr)}{Annual\ Load\ Served\ (kWh/yr)} = \frac{ASC}{E_{Total}} \quad (9)$$

### 3.4.4 Internal rate of return (IRR)

The internal rate of return, also known as the return on investment (ROI) or time adjusted rate of return is the true interest yield of the system during the project life. This is evaluated by setting the project NPV value to zero and then compute the discount rate.

### 3.4.5 Payback period (PBP)

This is the time period during which the initial investment (cash outflow) of the system is expected to be recovered from the investment generated cash inflow. It is given as:

$$PBP = \frac{Initial\ Investment}{Cash\ Flow\ per\ period} \quad (10)$$

### 3.4.6 Search Space

To find the optimum system architecture, search space in HOMER is utilized. The Search Space is where values, such as capacity or quantity, for various components are defined. HOMER uses these values to simulate all of the feasible configurations in the system and determine the most efficient configuration. The table below shows the search space for this system.

*Table 8: HOMER Search Space*

| Converter Capacity (kW) | Generator Capacity (kW) | PV size (kW) | Surr6CS25P Strings (Number) |
|---|---|---|---|
| 0 | 0 | 0 | Optimize |
| 100 | 100 | 150 | |
| 150 | | 200 | |
| 200 | | 300 | |

### 3.4.7 Sensitivity Variables

A sensitivity variable is an input variable for which multiple values can be specified. Parameters such as the price of fuel price, wind speed, temperature and solar radiation of the site may vary as a result of inflation (as in the case of fuel price) or climate change (as in the case of solar radiation, wind and temperature) and so, sensitivity variables needs to be specified to accommodate any change in the future. HOMER performs a separate optimization procedure for each specified value. The table below gives the sensitivity cases performed in this study.

*Table 9: Sensitivity Cases*

| Diesel fuel price (Naira/L) | Solar scaled average (kW/m2/day) | Temperature Scaled average ($^0$C) |
|---|---|---|
| 150 | 4 | 20 |
| 160 | 4.74 | 25.7 |
| 170 | 6 | 30 |

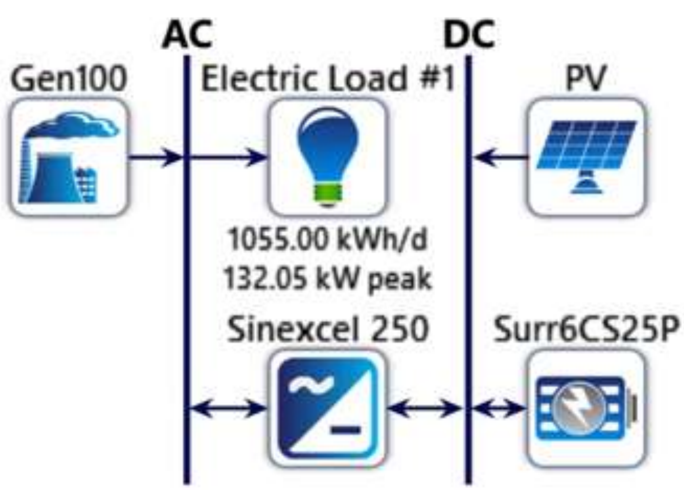
## Chapter Four

### 4.0 Results and Discussion

In this chapter, detail of the optimization results for the selected hybrid renewable energy system to meet a load peak demand of 135kW peak and 1055kWh/day consumption has been discussed. The design and optimization were carried out using the HOMER Pro Micro-Grid Analysis Tool (version x64.3.12.3) software. The optimum hybrid system theoretically and in many case design is defined as the system which can supply electricity at the lowest price or the system which have the total net present value and also that can supply the electricity constantly and sustainably. HOMER runs several simulations before the feasible system is identified based on the required output by the developer. The feasible solutions are presented in an increasing order of the net present cost from top to down. The categorized table presented the least cost effective combinations from among all components setup, whereas, the overall optimization results displayed all of the affordable system combinations based on their NPC. Hybrid systems are selected after simulation based on primarily minimum net present cost. Depending on the economic characteristics of the target customer base for the system, some other feature will be considered in the system selection process. Some of the selection parameters are: less cost of energy, high renewable fraction, low capacity shortage, low excess electricity generation, and less diesel fuel consumption could be used for comparison of power generating systems in order to check their technical and economic feasibility for the case location. One must avoid recommending a system for a community that cannot afford such system or do not want the system. Figure 34, shows a schematic representation of the hybrid system design with all the components under consideration. The schematic was generated by HOMER once the input data and components of the proposed system have been specified in the software.

### 4.1 Systems optimization scenarios

*Figure 32: Hybrid system schematics*



The following simulation and optimization scenarios in table 10 are proposed for detailed analysis to determine the optimum or the best hybrid system. The system with the a least positive NPC, least cost of energy (LCOE), more excess energy generation, higher renewable energy fraction, lowest fuel consumption and OPEX at the case location site should be chosen as optimum (it is also important to note the concerns of the shop owners and when selecting the final system) the cost to beat per month according the survey and interview feedback from the plaza is 700,000 Naira per month cost of electricity for the plaza. The goal of this research is to investigate if any of the considered scenarios can meet these requirements, hence helping business spend less on electricity. All the scenarios were optimized using the same data set.

*Table 10: Proposed study and optimization scenarios*

| **Proposed System** | **Scenarios** |
|---|---|
| PV/Battery/Diesel generator system | A |
| PV/Diesel generator system | B |
| PV/Battery system | C |
| Diesel generator/Battery system | D |

The comparison of the scenarios was performed based on the above stated technical measuring parameters. As a datum value to develop or structure the scenarios (most of which are worst cases), the following constraints was set on the software: the current diesel price of N160, maximum annual capacity shortage of 10%, scaled primary load of 135kW and scaled energy consumption of 1055kWh/day were inserted into the software. Figure 33 shows the categorised optimization result. The system component is shown in Table 11 below while the resources input data are shown in Table 12

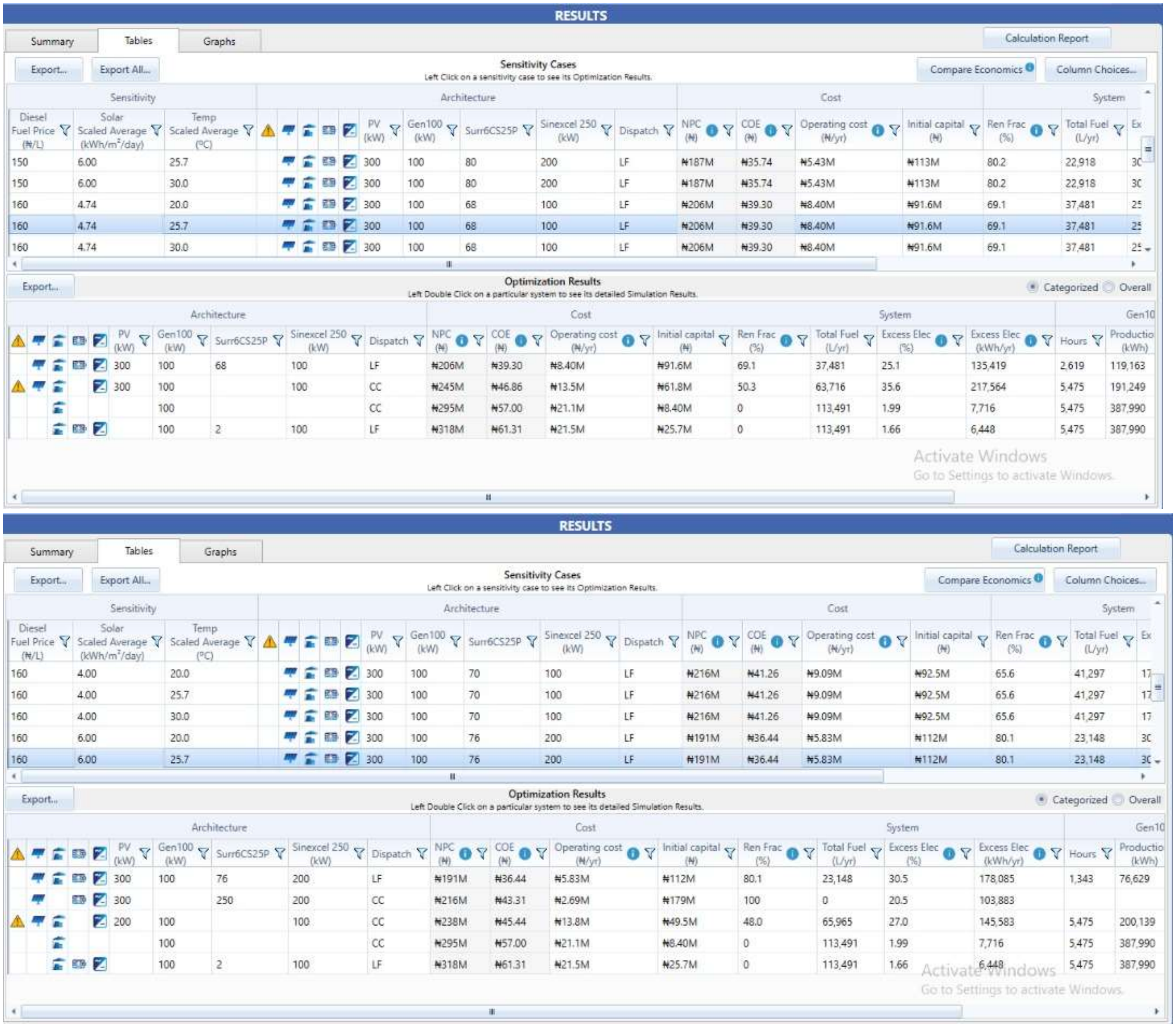
*Table 11: The system optimization components*

| **PV (kW)** | **Diesel Generator** | **Battery** | **Coverter** | **Dispatch Strategy** |
|---|---|---|---|---|
| 150/200/300kW | 100kW | Optimize | 100/150/ 200kW | Optimize |

*Table 12: Resources input data*

| Diesel Fuel price | Solar scaled Average | Temp. scaled average |
|---|---|---|
| N160/150/170/L | 4/4.74/6kWh/m$^2$/day | 25.7/20/30$^0$C |

*Figure 33: Categorized Optimization Results – HOMER interface*




| Gen100 | | | | |
|---|---|---|---|---|
| Hours | Production (kWh) | Fuel (L) | O&M Cost (₦/yr) | Fuel Cost (₦/yr) |
| 2,619 | 119,163 | 37,481 | 65,475 | 5,997,031 |
| 5,475 | 191,249 | 63,716 | 136,875 | 10,194,573 |
| 5,475 | 387,990 | 113,491 | 136,875 | 18,158,622 |
| 5,475 | 387,990 | 113,491 | 136,875 | 18,158,622 |

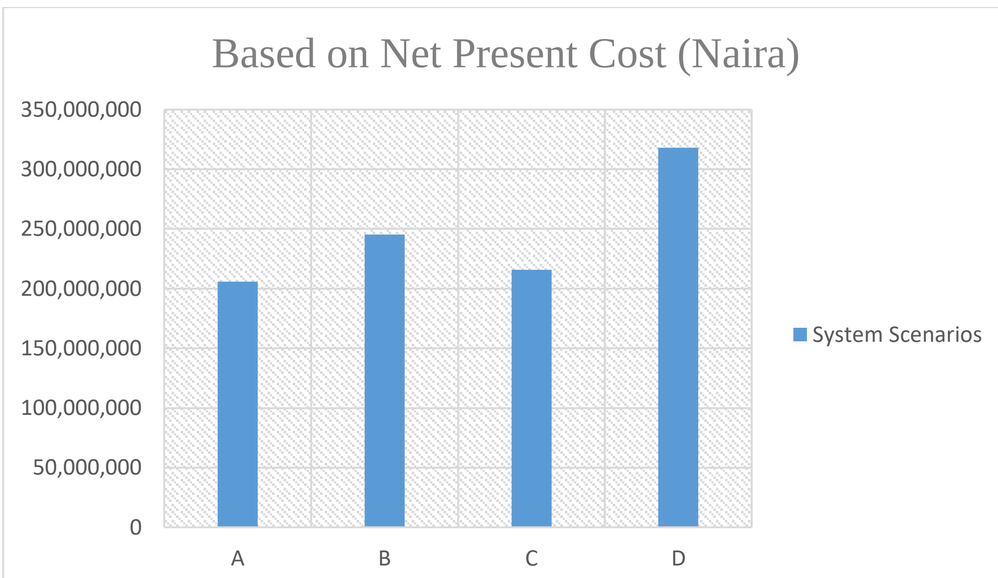
| Gen100 | | | | |
|---|---|---|---|---|
| Hours | Production (kWh) | Fuel (L) | O&M Cost (₦/yr) | Fuel Cost (₦/yr) |
| 1,343 | 76,629 | 23,148 | 33,575 | 3,703,612 |
| | | | | |
| 5,475 | 200,139 | 65,965 | 136,875 | 10,554,417 |
| 5,475 | 387,990 | 113,491 | 136,875 | 18,158,622 |
| 5,475 | 387,990 | 113,491 | 136,875 | 18,158,622 |

### 4.2 Comparison of Scenarios for Economic Power Systems

The optimum configuration was selected based on least positive net present cost (NPC), effective levelized cost of energy (COE), least initial capital (CAPEX), less operating and maintenance cost (OPEX), high renewable fraction, and less fuel consumption. For the case study, system CAPEX and the least possible LCOE (effective LCOE) that will ensure sustainability are the most desirable factors for the feasible system selection. For simplicity, the scenario with initial input data (N160/L, 4.74kWh/m$^2$ and temperature of 25.74$^0$C and for scenario C, the irradiance of 6 (because the HOMER simulation had no option for scenario C when the solar irradiance is considered at 4.74kWh/m$^2$) was considered for the result discussion and feasible system selection. For the full simulation data for all the considered case scenarios, see Appendix 3.

#### 4.2.1 Based on Net Present Cost (NPC)

*Figure 34: Comparison of Scenarios Based on Net Present Cost*

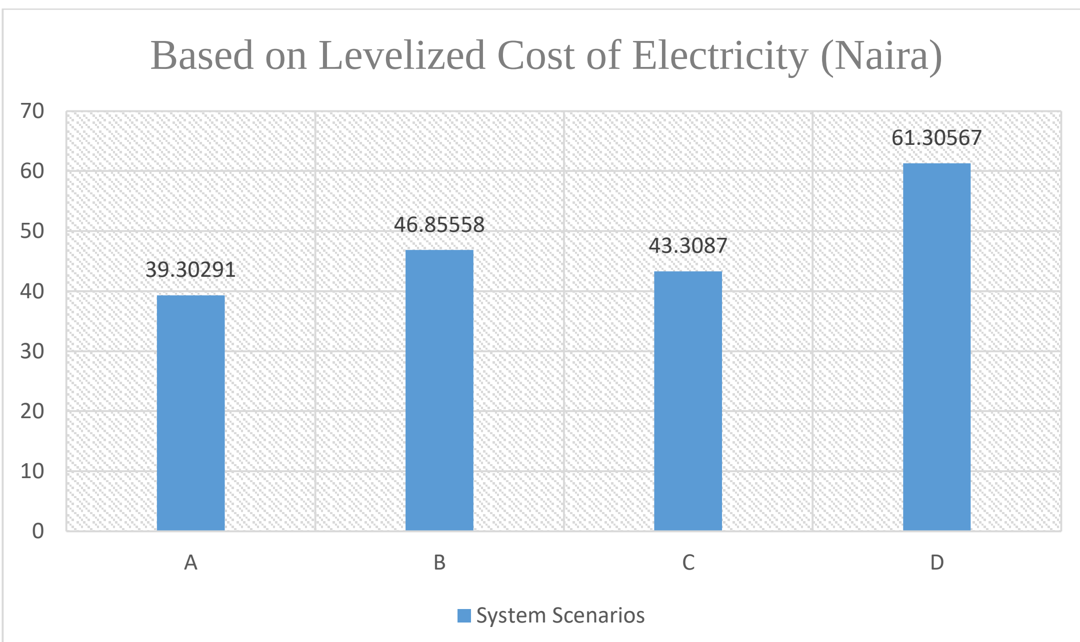



The less positive value the NPC is; the more economic desirable the system is. For these research, all system scenarios have a positive NPC – this means that they are for the least economically viable, but the system feasibility for every project is primarily based on end-user demand and ability to pay. It is also important to note that the economic significance of a hybrid system is not just determined based on its value of its NPC. Several other characteristics play an important role in the process of choosing a feasible system and in many cases, these factors are customer and case site characteristics – especially on the end-users' ability and willingness to pay for the electricity. From figure 34, scenario D has the highest value for the NPC followed by the B scenario with NPC values of 317,908,900 (Naira) and 245,284,400 (Naira) respectively. Because scenario D have the highest NPC in this simulation, scenario B have been selected for this work as a more feasible option than D because it has the required combination of renewable and conventional energy sources that this work target to achieve from the onset of this research.

### 4.2.2 Based on Levelized Cost of Energy (LCOE)

Figure 37 shows the levelized cost of electricity for the different simulation results. The four scenarios (A, B, C, and D) have different LCOE values with scenario D having the highest LCOE value of approximately 61.3 Naira. It is also shown on figure 37 that scenario A has the least LCOE value of 39.3 Naira. For this research case location, feedback from the shop owners indicate that they currently pay collectively 700,000 Naira per month as the cost for their electricity from their generator (for fuelling and maintenance). The goal is to make sure to get a system which can supply sufficient electricity to the plaza at a cost that is much less than the current cost which they pay and also which result in a reasonable system payback time. Careful consideration indicates that all the above Scenarios above is suitable in terms of cost of energy with the right amount of CAPEX for the individual systems. Also from the report made by REA, generally, it cost SMEs in Nigeria about 40 cents per kWh which is much higher than all the LCOEs of the scenarios. Therefore, even though scenario A has the least LCOE, it might still not be the system of choice based on what the value of its OPEX and CAPEX becomes. The effective LCOE will be calculated after all the various selected economic criteria has been evaluated.

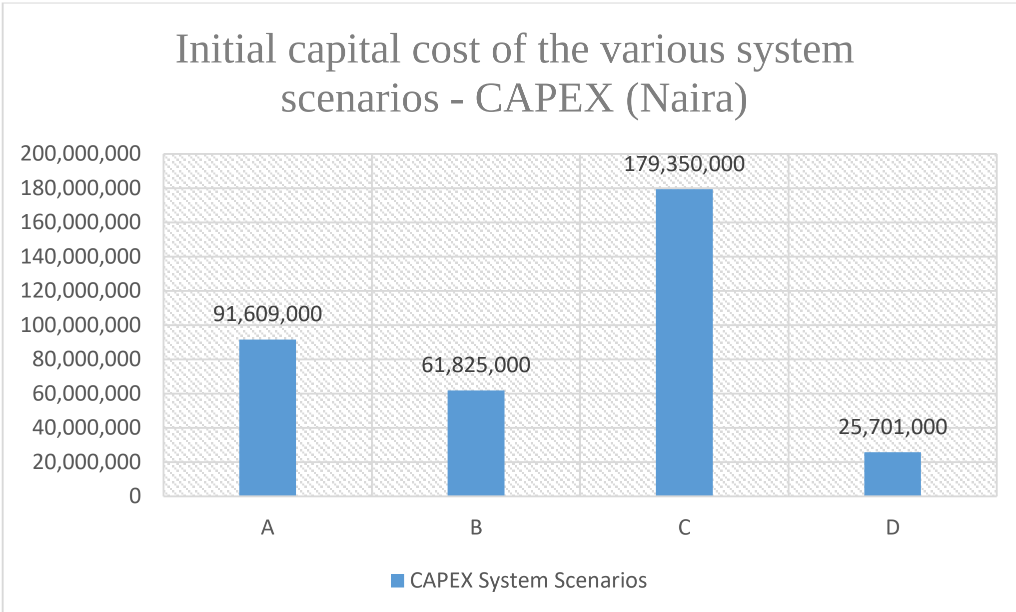
*Figure 35: Comparison of Scenarios Based on Levelized Cost of Electricity*




### 4.2.3 Based on Initial Capital Cost – CAPEX

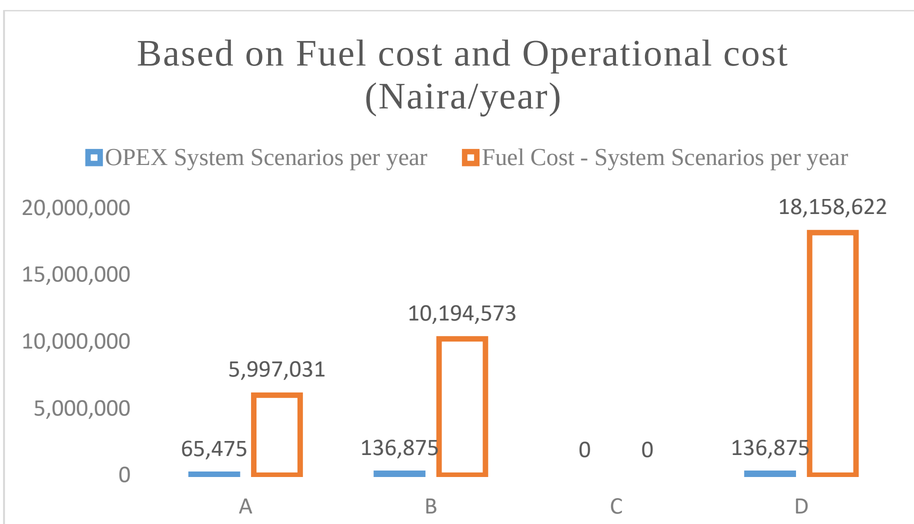
Based on the initial capital costs, Scenarios C and A has the highest initial capital cost, with C having a value higher than A. It becomes clear that when it comes to capital cost, scenarios A and C are not favourable because the small businesses cannot afford to pay-off such high cost of electricity in time. Scenario D has the least capital cost but with zero renewable fraction and therefore did not suit to the objective this research work wants to achieve. From figure 36, it can be seen that the most suitable scenario in this case is B. The CAPEX of 61,825,000 Naira is much feasible to implement for the considered case location for this study.

*Figure 36: Comparison of Scenarios Based on Initial Capital Cost*




### 4.2.4 Based on Fuel cost and Operational Cost - OPEX

*Figure 37: Comparison of Scenarios Based on Fuel cost and Operational cost*

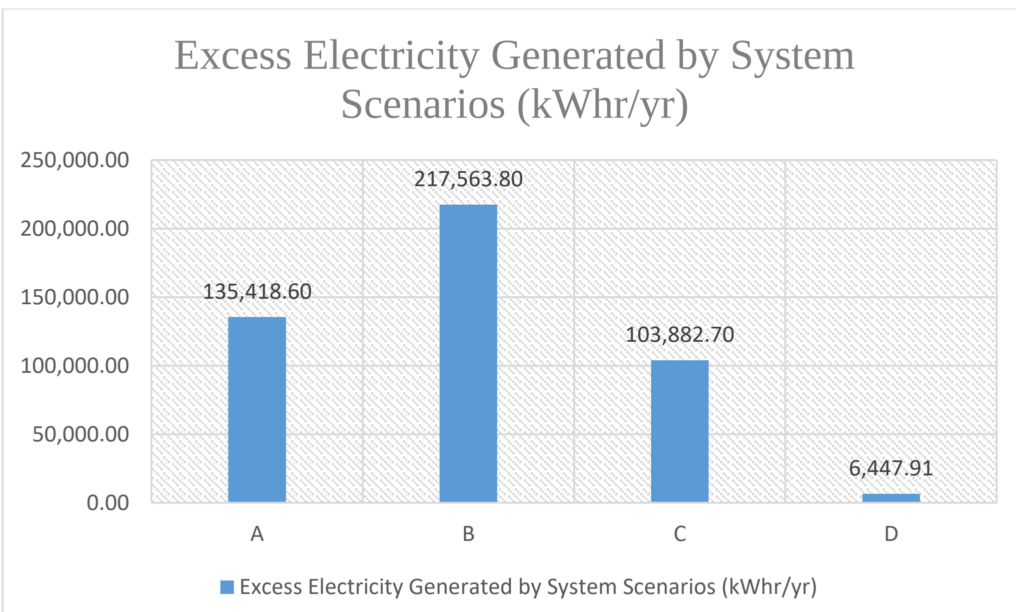



The fuel cost contributes immensely to the NPC and LCOE and other various costs for these systems. Although scenarios A, B, and D has diesel generator incorporated in them, the yearly cost of fuel and the yearly operating cost varies respectively for each of them. The most expensive being scenario D with a yearly fuel cost of over 18 million Naira and an operating cost of over

135,000 Naira. I should also be noted that the cost for the operating cost is only contributed by the generator fraction because the OPEX for the solar PV and battery is considered as zero. The reason for putting the OPEX cost for the renewable component maintenance as zero is because from the survey data as seen in Table 3, 63% of the shop owners and employees are at least secondary school educated and that the average age is 32 years. This research therefore recommends that some of the shop owners and employees are trained on the basic maintenance culture of solar PV components so that they will be able to service, maintain and replace the renewable components themselves whenever necessary, hence the zero value cost for OPEX in the HOMER software for renewables. The fuel cost and operational cost for scenario A is the least because of the high renewable fraction. Scenario B has a significant fuel cost and also a maintenance cost equal to that of D. the total estimated OPEX cost for scenario B assuming a project life of 25 years is 3,421,875 Naira. The value of the total project lifespan OPEX will be added to the CAPEX in other to estimate the effective LCOE, using the feedback from the field as a benchmark (Basing the cost of energy per month at 550,000 Naira which is well below the benchmark given by the shop owner, the **effective LCOE equals 21.73 (Naira/kWhr)**. This research recommends that the excess energy should be sold either in form of a feed-in-tariff back to the grid or to the nearby plazas in other to generate the needed cash for the yearly fuel cost for the feasible system. Therefore, the scenario with the most excess energy output will be very favourable in the implementation of this research and the need for favourable government policies like net-metering and feed-in-tariff should be in place as well.

#### 4.3.5 Based on the Excess Electricity Generated

*Figure 38: Comparison of Scenarios Based on Excess Electricity*

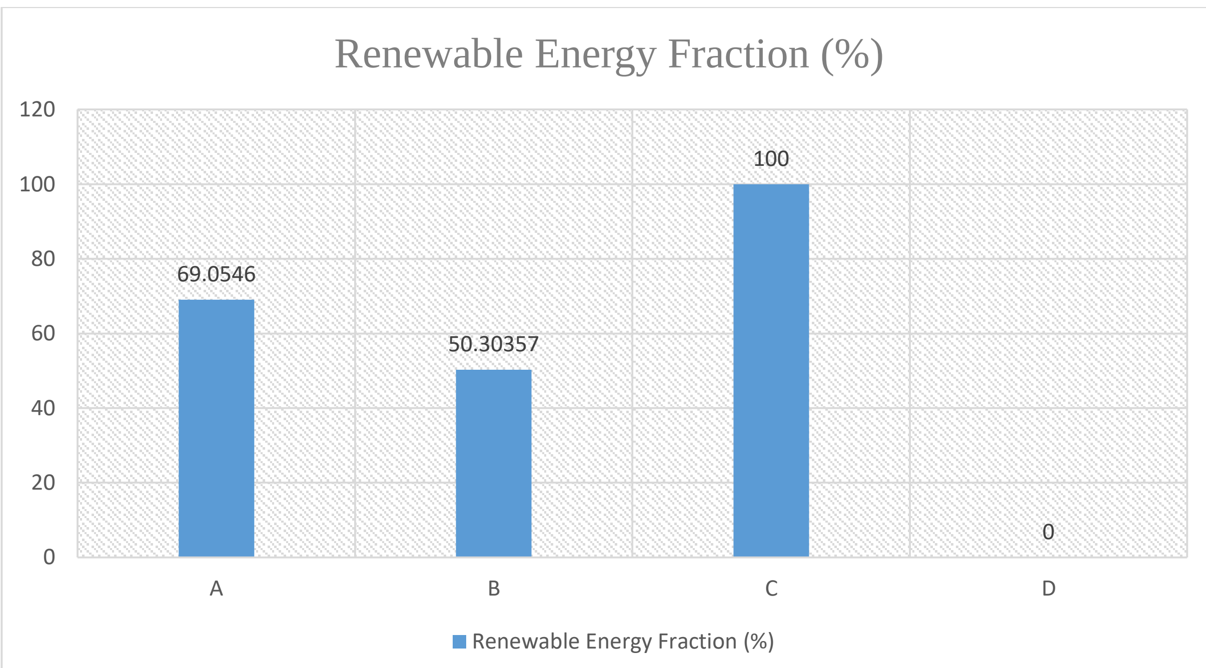



Excess electricity is surplus electrical energy that must be dumped (or curtailed) and in the case of this study sold, because it cannot be used to serve a load or charge batteries. Excess electricity occurs when surplus power is produced (either by a renewable source or by the generator when its minimum output exceeds the load) and the batteries are unable to absorb it all. This research has taken a different dimension and is considering the scenario with the highest excess energy generation possible as the most feasible scenario. This is because one of the major objective of this research is to investigate the feasibility of a renewable hybrid system that can provide electricity at an affordable cost to small businesses. Conventionally, systems with the lowest excess electricity production is considered as the optimal system but in this study, it is not. For this work, based on field data collected, it is seen that one of the only ways to have a feasible system is to sell the excess energy generated for profit to help with the system yearly fuel cost.

Scenario B is the clear highest with an excess energy generation of 217,563.80kWhr/year which if sold at an effective LCOE of 21.73 (Naira/kWhr) will result to a cash inflow of 4,727,661.374 Naira per year. Much of this cash can be used to support the cost of fuelling the generator for the year.

### 4.3.6 Based on Renewable Fraction (RF)

*Figure 39: Comparisons Based on Renewable Fraction*

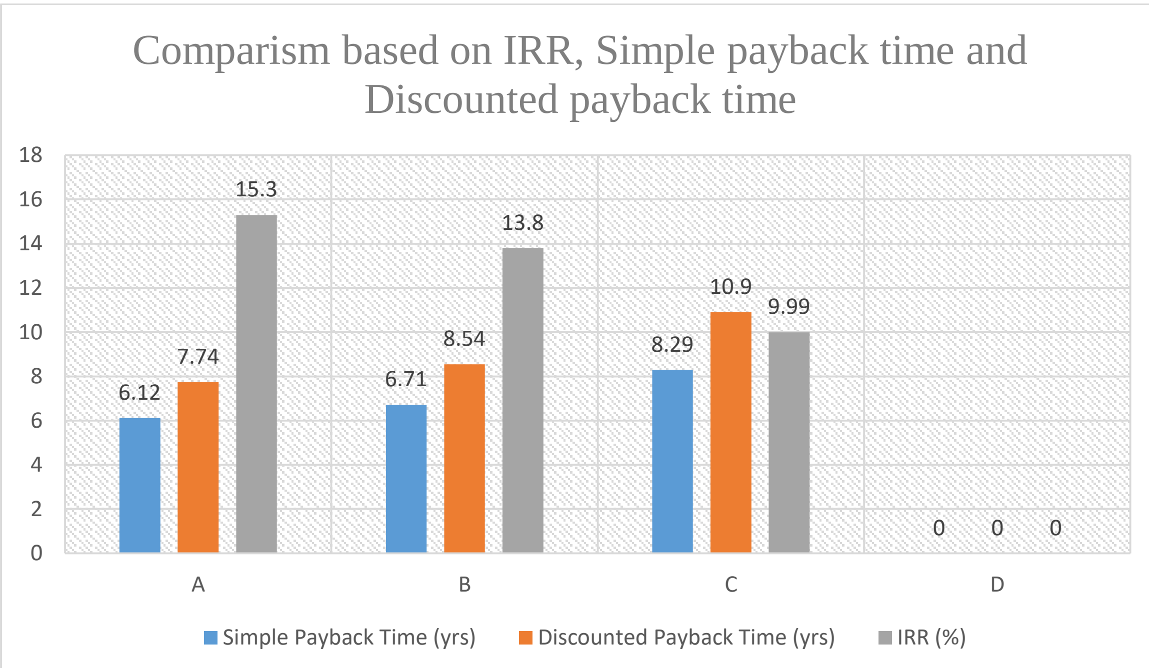



From figure 39, it is seen that the scenario C has a one hundred percent renewable fraction because of its very high initial capital cost, it will not be implementable for the case study for this research. Scenario A had a renewable fraction of approximately 69% but also a CAPEX of over 90 million Naira. The scenario of choice in this case will be scenario B which has an over 50% renewable fraction and a feasible CAPEX. Scenario Don the other hand has a renewable fraction of zero, which is not acceptable, resulting to high carbon dioxide, sulphur and more harmful gases into the atmosphere.

### 4.3.7 Based on Internal Rate of Return (IRR), Simple Payback and Discounted Payback

All the four scenarios are considered for this case are shown in figure 40. Scenario D is not applicable because it has close to zero renewable fraction (the battery was set to optimize and HOMER assigned just 2 sets of batteries to the generator battery scenario). The IRR and the discounted payback time is highest and least in scenario A respectively with values of 15.3% and 7.74 years respectively followed by scenario B which has an IRR of 13.8% but a higher discounted rate of return than scenario C. After every consideration, scenario B remains the optimal system recommendation. The effective LCOE of 21.73 (Naira/kWhr) was used to calculate the estimated simple payback time (not accounting for interest rates) and the result was approximately **9 years and 9 months**.

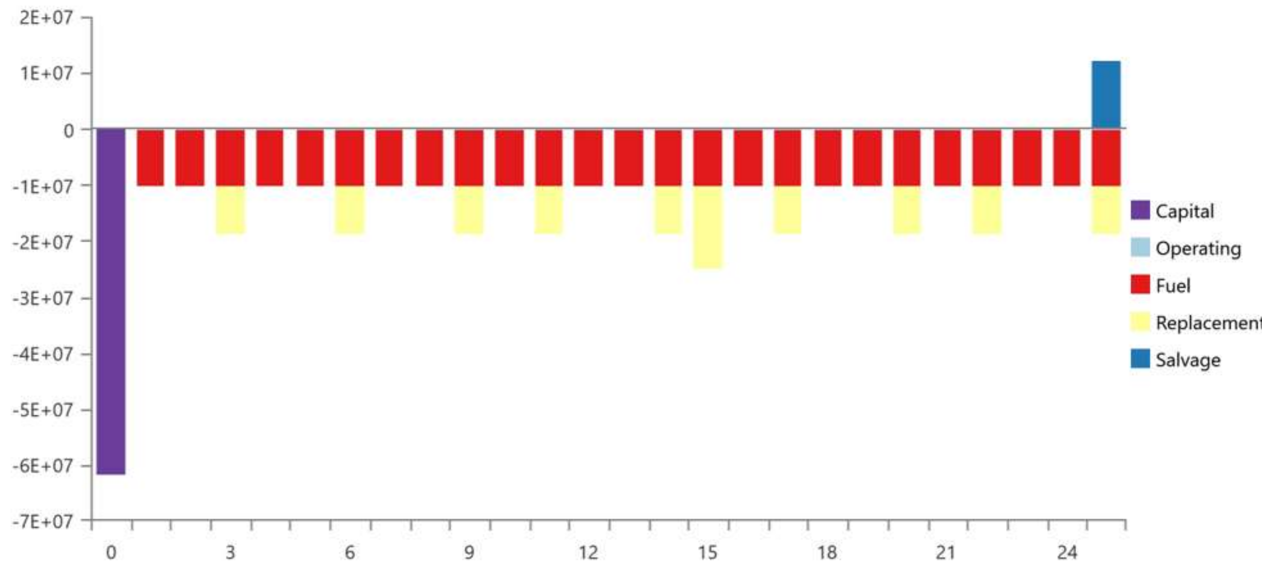
*Figure 40: Comparison based on IRR, Simple Payback and Discounted Payback*




From the careful consideration of the above comparisons in figure 40, scenario B is the system architecture that most suits the case study location for this research work. It also has the lowest initial capital cost and a considerable operating and maintenance cost. Based on these factors, we have concluded that among all the scenarios considered in this analysis, scenario B is the optimum hybrid renewable energy system the can supply adequate, reliable and affordable power to the businesses in Binitie plaza, computer village, Lagos Nigeria. This system is consisting only of Solar PV, Generating set, and a Bidirectional Converter. The NPC for this configuration is 245,284,400 Naira and the LCOE is 46.85558 (Naira/kWhr) of electricity. The effective LCOE was calculated for this system to be 21.73 (Naira/kWhr) of electricity. In the next section, the full system configuration and the effects of the various sensitivity variables on the NPC, CAPEX, OPEX, Excess Energy generation and on Carbon emission level will be discussed.

### 4.4 Optimization Analysis of the Selected Optimum Hybrid System

*Figure 41: System Lifespan Cash flow*




To analyse the optimal system, this section will focus on the various components of the system and also the entire system lifespan cash flow and the impact of the various sensitivity variables on the economic criteria of the system. The section will conclude by comparing the base system (genset) for the case study with the recommended optimal system to highlight some of the environmental and economic benefits the business owners stands to gain if their electricity is supplied from the recommended feasible system. From figure 41, it is seen that for the first year, it will cost the capital investment cost of over 61 million Naira in other to develop the system. Once the system is operation, majority of the system cost will come from the fuel cost which is about 10 million naira yearly and a few replacement cost. HOMER estimate the system salvage value at the end of its lifespan to be around 10 million naira. The recommended implementation strategy is to insure that there are favourable government policies that will support feed-in-tariff schemes to provide the framework which excess energy generated can be sold back to the grid or to the nearby plazas and the cash inflow used to support the yearly fuel cost.

#### 4.4.1 Electricity Generation and Load Demand – Excess and Unmet

One of the reasons for selecting this system as the feasible alternative for the supply electricity to the shop owners at Binitie plaza in Lagos Nigeria is the fact that, due to the nature of the yearly irradiance profile of the location, the system can generate an excess energy of 217,564kWhr/yr as shown in table 13. Therefore, for the full implementation of this system to be economically viable, government policies that enables feed-in-tariff agreements with the DISCO in charge of the location (Ikeja Electric) to guarantee the sale of the excess energy through an agreed Power

Purchase Agreement (PPA) will be vital. The cash inflow from the sale of electricity either through feed-in-tariff or to nearby plaza will be a source of the need revenue that can help reduce the yearly cost of fueling the generator. The unmet electric load is in other hand not desirable and has to be mitigated. As seen from figure 30, the yearly solar irradiance of the location can be quite very low as much as 4kW per square metre around the month of June, July August and September. These result to low power output from the solar cells leading to unmet demand (hence the capacity shortage of 4,101kWh/yr). The choice of generating set for this research was set at 100kW in other to reduce the likelihood of over sizing. Our recommendation will be for the size of the genset to be increased to the peak demand which is 135kW in future simulations in other to account for the shortfall in yearly demand.

*Table 13: Excess and Unmet Electricity Generation and Load*

| Quantity | Value | Units |
|---|---|---|
| **Excess Electricity** | 217,564 | kWh/yr |
| **Unmet Electric Load** | 240 | kWh/yr |
| **Capacity Shortage** | 4,101 | kWh/yr |

### 4.4.2 PV/Generator Electrical Power Production and Supply Analysis

The production capacity and distribution of electricity production by the solar PV and the generator is shown in table 14 below. From table 14, we can see that over 68% of the yearly energy generated is provided by the PV while the remaining 31% provided by the generator – resulting to a combined yearly production rate of 610,721kWh/yr, almost twice the estimated yearly ac load demand of the case location. The mean output of this PV is 1,149kWh/day – this means that the average power generated from PV can supply adequately the maximum consumption of the establishment (estimated to be 1055kWh/day) except for the low irradiance months.

*Table 14: Production and Consumption Summary*

| Component | Production (kWh/yr) | Percent |
|---|---|---|
| **Generic flat plate PV** | 419,472 | 68.7 |
| **Generic 100kW Fixed Capacity Genset** | 191,249 | 31.3 |
| **Total** | 610,721 | 100 |
| **AC Primary Load** | 384,835 | 100 |
| **DC Primary Load** | 0 | 0 |
| **Deferrable Load** | 0 | 0 |
| **Total** | 384,835 | 100 |
| **Mean Output of PV** | 1,149 | kWh/d |

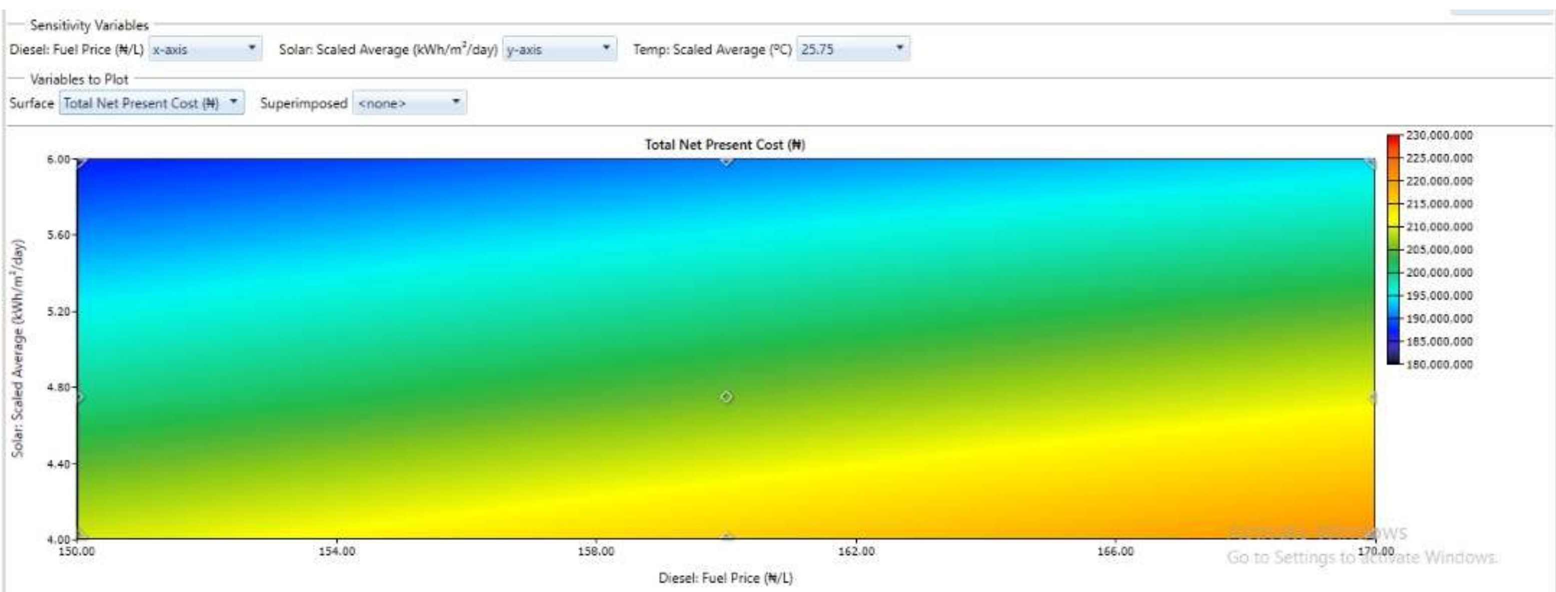
### 4.5 Effects of sensitivity parameter variations on system's economic selection criteria

Through a careful examination of the full simulation data in Appendix 3, we have realized that the temperature sensitivity variation had no effect on the economic criteria of the system. This is because the range of temperature change is not significant. This section will only focus on the changes as a result of the irradiance and the fuel coat variations on the economic criteria, while the temperature is constant at $25.75^0$C.

#### 4.5.1 Effect of Sensitivity variation on Net Present Value (NPC)

As seen from figure 42 in the simulation plot from HOMER, an increase in the cost of fuel 170 Naira, will result in an NPC maximum value of 280 million Naira – which is not desirable for this system. While an increase in the solar irradiance to 6kWh per square metre per day will result to a much economical value for the NPC at 180 million Naira. This is because, a higher irradiance means more output power from the solar module and less use of the generator.

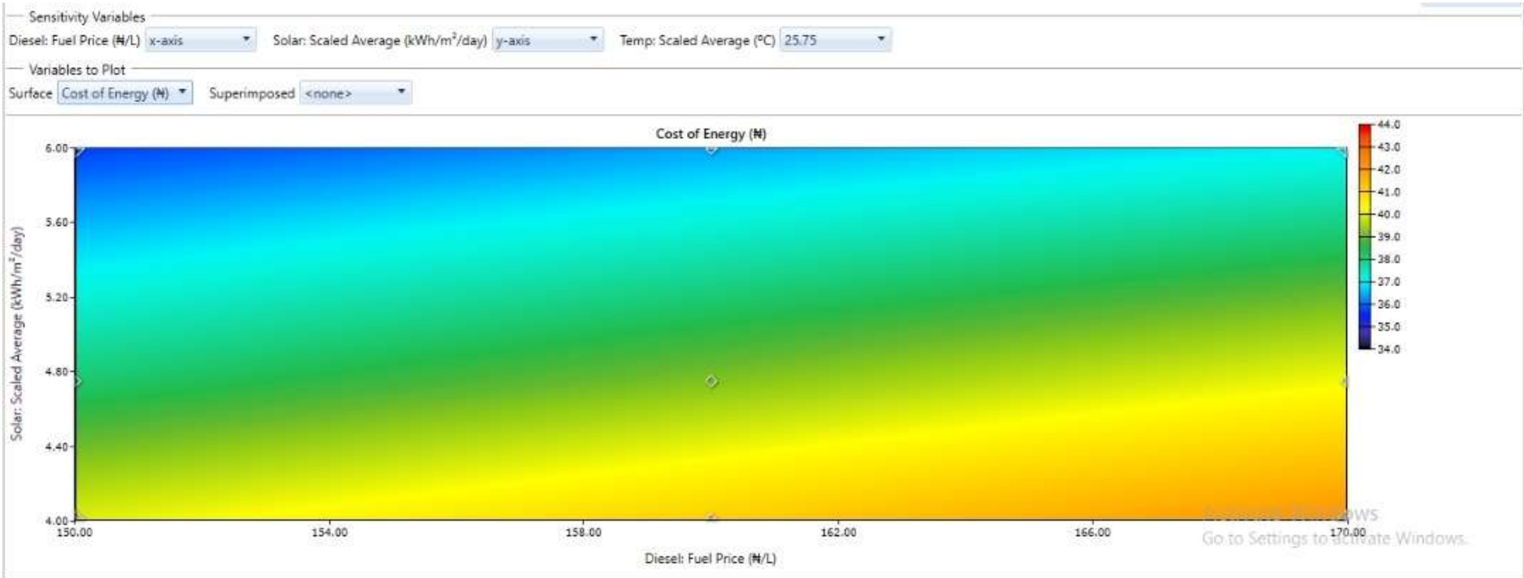
*Figure 42: Sensitivity variables plot against total Net Present Value (NPC)*




#### 4.5.2 Effect of Sensitivity variation on the Levelized Cost of Electricity (LCOE)

As similar trend is seen in figure 43 as was seen in figure 42 above. The higher the fuel cost, the higher the LCOE. While the higher the solar irradiance, the less the LCOE. A higher irradiance for solar solar energy production is always desirable, so long as it does not come at the cost of the environment with increase in atmospheric temperature and climate change.

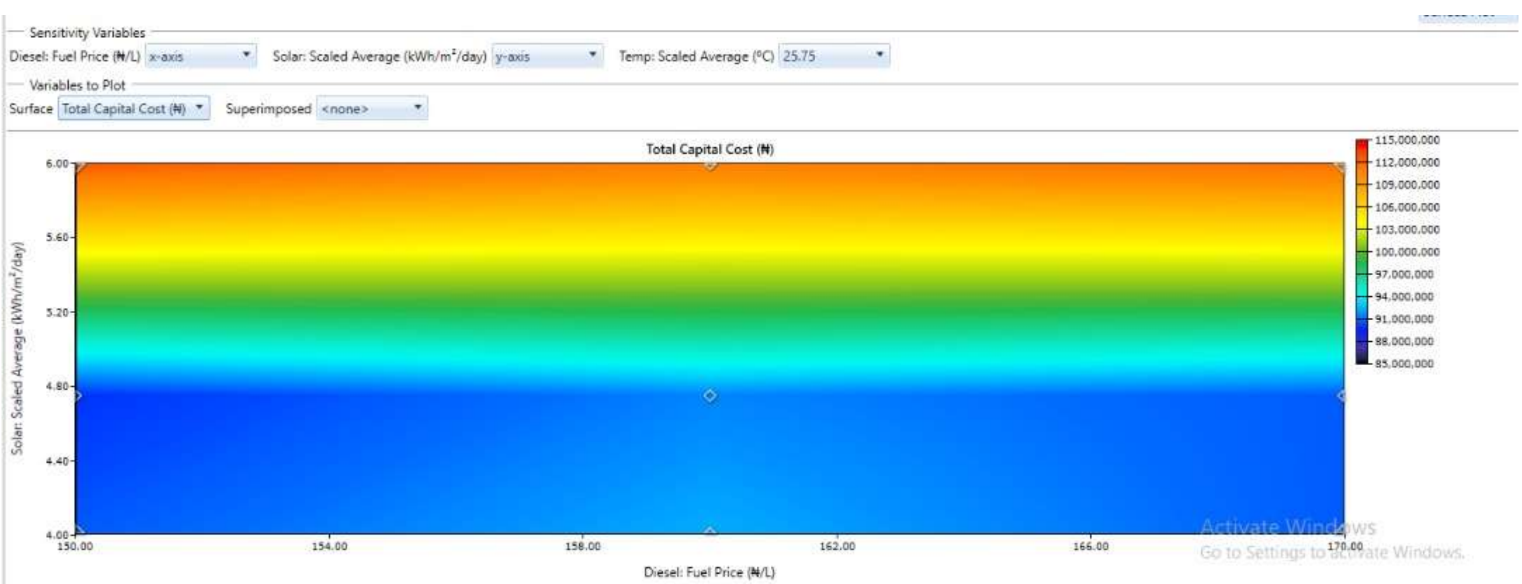
*Figure 43: Sensitivity variables plot against the Levelized Cost of Electricity (LCOE)*




## 4.5.3 Effect of Sensitivity variation on Initial Capital Cost – CAPEX

From figure 44, it is seen that the higher the solar irradiance, the higher the initial capital cost and that the fuel cost have very little influence in the capital cost. Also, the capital cost for this system remains relatively the same around the irradiance value of 4 – 4.8kWh per square metre regardless of what the fuel cost is, but increases after 4.8 – reaching a maximum of 115 million Naira at the irradiance of 6kWh per square metre. This is because majority of the capital cost for a solar PV hybrid system is contributed by the PV system.

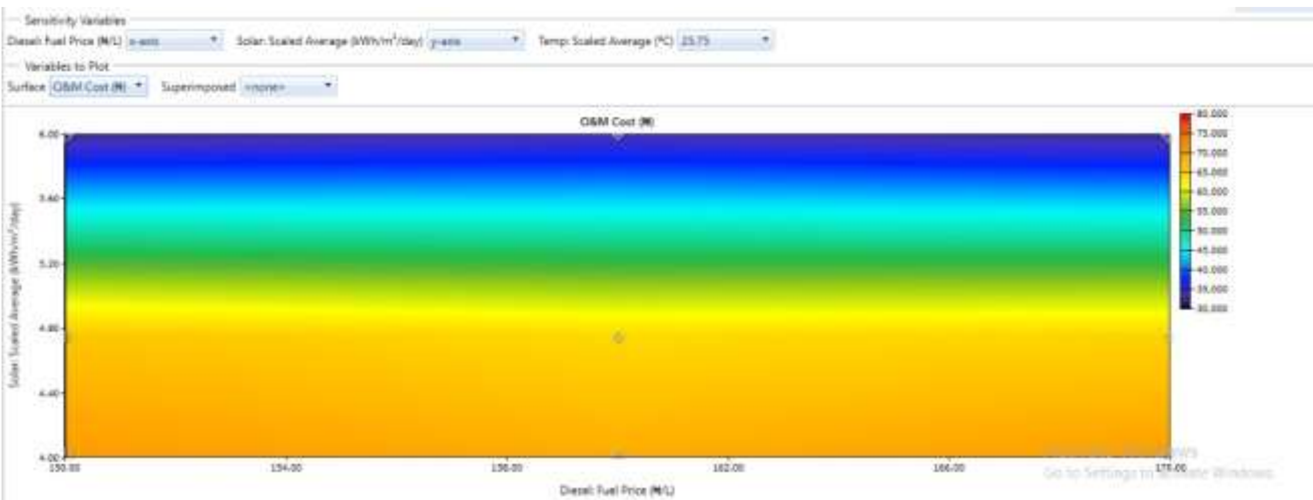
*Figure 44: Sensitivity variables plot against the total Initial Capital Cost - CAPEX*



### 4.5.4 Effect of Sensitivity variation on the Operation and Maintenance Cost - OPEX

From figure 45, the simulation results show in the plot is as expected. One of the implementation strategy recommendation of this research is the training of some of the educated shop owners on the maintenance culture of PV system components so as to eliminate the cost of PV operation and maintenance. We can see from the plot that the OPEX is contributed by only the generator and that the only way the cost can be reduced or increase will be in a case where the solar irradiance increases, leading to a higher power generation output from the PV and a less use of the generator.

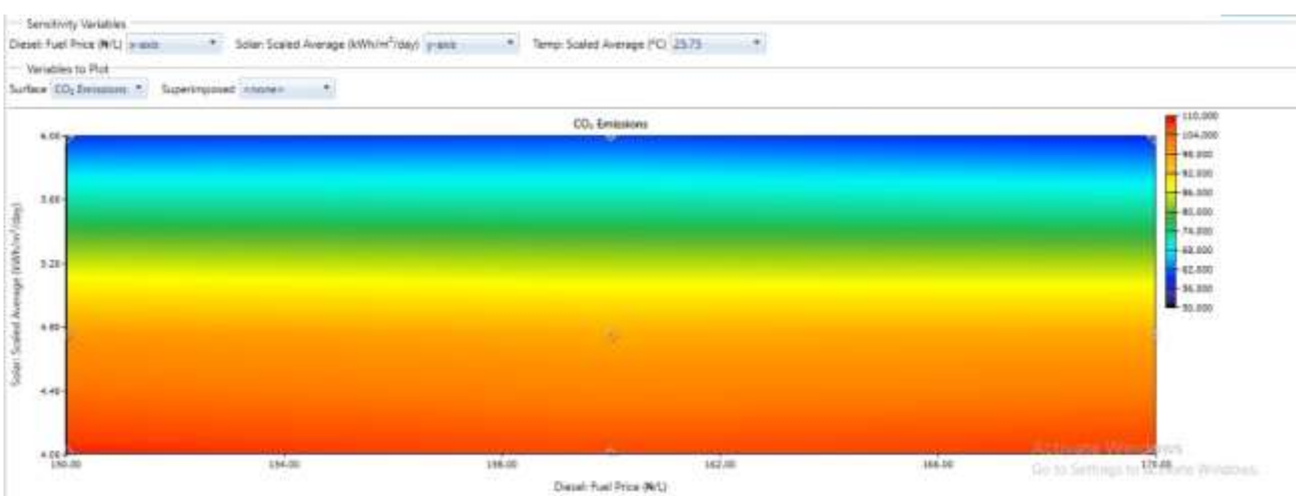
*Figure 45: Sensitivity variables plot against the Operation and Maintenance Cost – OPEX*




### 4.5.5 Effect of Sensitivity variation on $CO_2$ emissions

Figure 46 shows that the lower the solar irradiance, that more the generating set is used and this results to more pollution of the environment with $CO_2$. For a significant reduction on the $CO_2$ emission level for the system, the irradiance level show be at least 5.20kWh per square metres.

*Figure 46: Sensitivity variables plot against CO2 emissions*



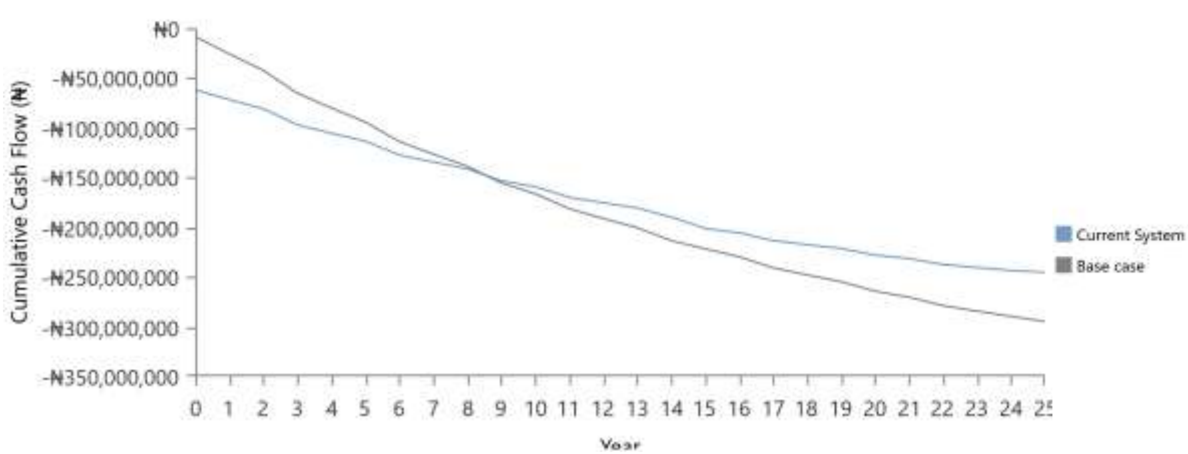
### 4.6 Compared economics between the base system and the proposed feasible alternative

*Table 15: Compared Economics – Base Case and Optimal System*

| | Base Case | Current System |
|---|---|---|
| **Net Present Cost** | ₦295M | ₦245M |
| **CAPEX** | ₦8.40M | ₦61.8M |
| **OPEX** | ₦21.1M | ₦13.5M |
| **LCOE (per kWh)** | ₦57.00 | ₦46.86 |
| **CO2 Emitted (kg/yr)** | 296,846 | 166,655 |
| **Fuel Consumption (L/yr)** | 113,491 | 63,716 |

From table 15, the estimated NPC, CAPEX, OPEX, $CO_2$ emitted and the resulting fuel cost is well compared. From all indication, the recommended optimal system for the shop owners in the case study location for this research performs much better than the base (which is the means of electricity generation already in use at the plaza). One of the most significant benefit of the optimal system is the reduction of $CO_2$ emission to the environment and also the reduction in noise pollution which constant use or generator set causes. The resulting reduction in $CO_2$ emission that will come from the use of the recommended system will be 44%. A nearly 50% reduction in $CO_2$ is significant. The impact of system externalities is significant in Nigeria but still the government of Nigeria has not implement policy as require as a signatory to the Paris Climate Agreement. Carbon taxing policies will encourage more investment into system such as the one recommended and incentives to developers who invest in renewable and environmental friendly energy generation will greatly help to change the dynamics of the energy landscape in Nigeria. Figure 47 shows the plot of the cash flow between the base system and the optimal system for the lifespan of 25 years. It can be seen that the most significant investment that is needed for the optimal system is the initial capital cost of about 61 million Naira and that subsequent years the optimal system running cost is much cheaper than the Base system – resulting in a lot of saving overall of up to 50 million Naira.

*Figure 47: Discounted Cash Flow - Base Case and Optimal System*



**Chapter Five**

## 5.0 Conclusions and Recommendation

Throughout the four previous chapters in this report, this research work has tried to highlight the importance of MSMEs to national GDP and overall national development. The factors that hinders the growth of MSMEs was subsequently looked into in chapter one and among these challenges is the issue of poor energy access. Several literatures which have written extensively on the challenges of SMEs (especially in Sub-Saharan Africa) were cited. The report focused on the issues of poor and expensive energy access for businesses in Africa; with Lagos Nigeria as the case study location. Chapter two explored more literatures on the energy landscape of Nigeria and of Africa in general – citing cases of mini-grid development, the challenges and opportunities that lies ahead of it for investors. The energy resource potentials in Nigeria was also discussed in chapter two – mostly focusing on the renewable energy potentials and the opportunities for investment in the country. This research then went ahead to investigate the feasibility of providing a feasible hybrid mini-grid system (as the topic suggest) for small businesses in Nigeria, using a model cluster market in Computer Village Business District in Lagos Nigeria – Binitie Plaza as the case study.

The research methodology was developed in chapter three based on the established mini-grid sizing and design methodology developed by the GIZ. Similar model was followed for this research and a field visit to the case study site was carried out for data collection and in-person interviews with the business owners and the leadership of the plaza. A documentary of the site visits and interviews was subsequently developed and is now uploaded to *Donald Chidera Abonyi's Youtube page.* With the collected data, the HOMER Pro simulation software was used to model for a feasible system – towards achieving the set objectives of this study. A PV/Gen hybrid system was identified to be the optimal system for implementation in a case like Binitie. The optimal system is also adaptable to similar sites all around Nigeria or any location in Sub-Sahara Africa with similar environmental conditions and economic activities. Chapter four has a detailed discussion of the simulation results and also of the other data that helps to inform on the possible implementation strategy and end-users demand-side management approaches – such as the consumption behaviour, education level and knowledge of energy efficiency measures. Four major objective were set out to be achieved through this research. These objectives include:

- To investigate the techno-economic possibilities of integrating solar PV mini-grid system within the existing network for SMEs in Lagos Nigeria at a rate less than 40 US cent/kWh

For the first objective above, through this study, a feasible solar PV hybrid mini-grid has been identified to be suitable both technically and economically at an effective LCOE of 21.73 Naira per kWh of electricity. The system is a hybrid of solar PV and generator. The LCOE of 21.73 Naira is equivalent to 6.04cents/kWh for the price of electricity.

- To investigate the impact of the use of Solar PV hybrid system (mini-grid) on business profitability, employability and environmental impact

The Binitie plaza has an estimated peak daily consumption of 1055kWh/day. At a consumption rate of 1055kWh/day, it will cost the plaza 550,000 Naira ($1,517.40) monthly for electricity with the new system. The plaza will be making a savings of about 150,000 Naira ($413.84) monthly from the initial cost of electricity which was 700,000 Naira per month. A cost saving of 150,000 Naira ($413.84) for an estimated 200 shops in the plaza will result to a monthly added profit of at least 750 Naira ($2.07) to every individual shop owner in the plaza. This also means more money can be saved by the business owners and can also lead to more hiring of employees and a lesser chances of businesses closing down because of poor revenue generation. From the HOMER simulation, it can also be seen that the use of the optimal system will lead to drastic reduction in carbon dioxide emissions up to 44%. This is of great benefit to the environment and also contributes to the fight against climate change. The recommended system also reduces noise pollution as well.

- To identify the most cost-effective system design (PV/Diesel/Battery – hybrid mini-grid system)

A feasible mini-grid hybrid system of Solar PV and Generator of initial capital cost of ~61 million Naira (~$168,292.90) and a simple payback time of 9 years and 9months was identified. The selling price of 21.73Naira/kWh ($0.06/kWh) of electricity was also estimated for the optimal system. This objective is therefore considered to have been achieved.

- To develop a financial model that is suitable for different business sectors based on their revenue stream and location, to ensure community capacity building and demand-side management implementation approach.

The initial LCOE that the HOMER simulation gave was above 41 Naira/kWh of electricity and would have resulted to a monthly electricity cost of over 1 million Naira for the shop owners at Binitie plaza. A new payment model was then developed based on the feedback from the leadership of the plaza and a much effective LCOE calculated based on the shop owners' ability and willingness to pay data. The education level of the business owners and employees was also determined and with that, the implementation strategy of training some of the shop owners or employees who have at least secondary education to support in the management and maintenance of the solar PV component was used in the simulation model; resulted in zero OPEX for the PV components and also will ensure community capacity building and demand-side management for the project – ensuring the sustainability of the system throughout it lifespan of 25 years.

Sensitivity analysis was also carried out for the system, three sensitivity cases were used for three different parameters (temperature, average solar irradiance and fuel cost). It was observed as seen in Appendix 3 that for small range of temperature changes, the variation in simulation output is insignificant. The effects of all the considered sensitivities was discussed in chapter four of this report. It is also important to note that the optimal system can be deployed in any similar case location in Nigeria with similar or more favourable climatic condition and economic activities. The same applies to any other location in Africa.

Finally, this research concludes by stating that the most important parameter in the understanding of the energy situation of small businesses in Africa and Nigeria in particular, is in the ability to collect a well-informed primary data on the situation on the ground and to make sure to involve the business owners in any implementation strategy. With the right set of consumption, demand and distribution energy infrastructure data, the most technically and economical viable solution can be provided for any given site location. This research recommends strong policy frameworks such as feed-in-tariffs, net-metering and contractual binding PPAs to be put in place in other to provide favourable environment for investors to confidently invest in the energy landscape of small business in Nigeria. If good policies are not in place to encourage and help caution the risk of investing in off-grid renewable energy systems, then it will largely still be government agencies and International grant donors who will continue to have the capacity to make significant invest in the mini-grid sector of the economy. It is important to note that without good policy implementations as recommended above, the optimal system from this research will still not be economically viable for small businesses.

I believe that with proper and well integrated electrification planning, no African country will be left behind in the actualisation of the United Nations SDG7 goal - towards 100% sustainable energy access rate in the world. I recommend for neighbouring countries (who have not yet) to see how to carefully interconnect their power grids and trade electricity with complete transparency and a decentralised energy value chain that will put into consideration all available resources in their region. I'm fairly certain that a data driven electrification planning in Africa, has the potential to replicate similar success (or even more) which has been recording in the global aviation industry - by following similar model of collaborative distribution planning.

## 5.1 Recommendations for future studies

- This study used NASA satellite datasets for the study sites. Future studies should consider using measured ground data for more precision or data collected from the countries space agency.
- The wind resource of the site location is low, therefore systems with wind components are not advisable for economic reasons.
- HOMER optimization involves complex simulation, optimizations and sensitivity analyses. Thus, in complex system designs (systems with many components), it is recommended to use high capacity and processors computers.
- Developing an energy management system for the mini-grid and also a load sharing and shading framework especially in the low irradiance months is recommended.
- Proposing a suitable operation and maintenance scheme which can ensure the sustainable operation of the system.

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