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Quantifying the challenges associated with poor electricity supply in Nigeria and the role of a hybrid PV system in addressing them

Thesis presented by

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Table of Contents

List of Figures and Tables vi
Declaration ix
Dedication x
Acknowledgement xi
List of Articles, Conferences attended, Presentations and Publications xii
Abstract xiv
Glossary of Terms, Abbreviations and Acronyms xv

Chapter One – Introduction

1.1. Research background 2
1.1.1. Problem statement 3
1.1.2. Research objectives 3
1.2. Research approach 4
1.2.1. Philosophical worldview 4
1.2.2. Exploratory sequential mixed method 4
1.3. Expected contribution 5
1.4. Research structure 6
1.5. Conceptual framework 8

Chapter Two – Nigeria’s energy sector: An overview

2.1. Background on Nigeria 10
2.1.1. Climate and weather 11
2.1.2. Economic situation 11
2.1.3. Population density and regional distribution 12
2.2. Nigeria’s power sector 12
2.2.1. Oil and gas subsector 14
2.2.2. Renewable energy subsector 15
2.2.2.1. Renewable energy resource availability 18
2.2.2.2. Renewable energy deployment rates 19
2.2.2.3. Renewable energy deployment limitations 20
2.2.2.4. Energy use in Nigeria 20
2.3. Initiatives, plans and programmes aimed at improving electrification 21
2.4. CO_2 emissions from the energy sector in Nigeria 22
2.5. Issues arising 22
2.6. Research questions 23
2.7. Summary 23

Chapter Three – Methods

3.1. Case study presentations 25
3.2. Interviews, Questionnaires and Surveys 28
3.3. Qualitative and Quantitative analysis 31
3.4. Numerical simulation 35

Chapter Four – The economic impact of unreliable power supply in Nigeria

4.1. Introduction 41
4.2. Nigeria's electricity sector 43
4.3. Method 47
4.3.1. Case study presentation – The cost of unreliable grid power on manufacturing in Nigeria 47
4.3.1.1. Data presentation 47
4.4. Analysis 50
4.4.1. Scenario development 55
4.4.2. Assumptions 55
4.4.3. Scenario selection 56
4.5. Discussion 57
4.6. Limitations 64
4.7. Conclusions 64

Chapter Five – Public awareness and societal acceptance of Renewable Energy in Nigeria

5.1. Introduction 67
5.2. Interview definition – Impact of power supply on business operations in the multi-sectors 67
5.3. Interview findings 69
5.4. Survey presentation and analysis – Survey of Abuja city residents' energy usage and renewable energy awareness 72
5.5. Survey findings 75
5.6. Summary of social studies 76
5.7. Justification of the methods adopted in conducting the social studies 77
5.8. Limitations of the studies 78

Chapter Six – Practical solutions for increased electrification, lower emissions and lower energy costs in Nigeria

6.1. Introduction 86
6.2. Review of relevant studies 88
6.2.1. Energy solutions 88
6.2.2. Energy access drivers 90
6.2.3. The gaps in the literature 92
6.3. Method 93
6.3.1. Survey on commercial centres 95
6.3.1.1. Load demand projection/determination 95
6.3.2. Power system selection and cost consideration 96
6.3.2.1. Solar-PV system 96
6.3.2.1.1. Solar-PV system cost consideration 97
6.3.2.2. Battery storage system 97
6.3.2.2.1. Battery storage system cost consideration 97
6.3.2.3. Generator system 98
6.3.2.3.1. Generator system cost consideration 98

6.3.3. System operations of the different IPS 99
6.3.3.1. Rationale for the IPS' operations design, planning and management 100
6.4. Results 101
6.4.1. Sensitivity analysis of the battery lifetime 103
6.5. Discussion 107
6.6. Limitations of the study 109
6.7. Conclusions 109

Chapter Seven – The transition to an energy autonomous multi-sector

7.1. Introduction 118
7.2. Review of relevant studies 119
7.2.1. The viability of grid defected power system solutions 120
7.2.2. The factors considered when designing grid defected power system solutions 121
7.2.3. How the choice of power system solutions explicates the difference between the energy landscape of advanced economies and emerging economies 125
7.2.4. The knowledge gap 127
7.3. Method 128
7.3.1. Design consideration for power systems' performance analysis 129
7.3.1.1. Solar resource 129
7.3.1.2. Load demand determination 129
7.3.1.3. Technologies considered 129
7.3.2. Metrics considered for power systems' performance assessment 130
7.3.2.1. Technical assessment (Reliability) 131
7.3.2.2. Economic assessment (Affordability) 131
7.3.2.3. Environmental assessment (Sustainability) 132
7.4. Results 135
7.4.1. Categorisation of all solutions 135
7.4.2. Categorisation of theoretical solutions – 2nd order of systems elimination 136
7.4.3. Categorisation of practical solutions – 3rd order of systems elimination 137
7.4.4. Optimum power system solution – 3rd order of systems elimination (1st priority level) 137
7.4.5. Summary of results 139
7.5. Discussion 142
7.6. Conclusions 143

Chapter Eight – Conclusions

8.1. Theoretical and Practical contributions 146
8.1.1. Theoretical contributions 146
8.1.2. Practical contributions 147
8.2. Implications of the research approach 148

8.3. How the thesis answers the research questions and meets the objectives 149
8.3.1. Research questions 149
8.3.2. Research objectives 151
8.4 The way forward – some recommendations 153
8.5. Further work 155

References 156
Bibliography 169
Appendices 170

List of Figures and Tables

Figures

Figure 1.1 – Framework of the research approach 4

Figure 1.2 – Conceptual framework of the research 8

Figure 2.1 – Map of Nigeria showing its land borders and the Federal Capital Territory 10

Figure 2.2 – Map of Nigeria showing population density of persons per km^2 12

Figure 4.1 – Map of Nigeria showing population and power plant distribution 44

Figure 4.2 – Number of system collapses over the years 46

Figure 4.3 – Infographic on the implication of the results 63

Figure 5.1 – Illustration of the implications of the results from the interview-driven social study 71

Figure 5.2 – Visual representation of select data from Table 5.2 74

Figure 6.1 – Silverbird entertainment centre, Central Business District, Abuja, Nigeria 81

Figure 6.2 – Wuse market, Wuse 2, Abuja, Nigeria 81

Figure 6.3 – Banex plaza, Wuse 2, Abuja, Nigeria 82

Figure 6.4 – Commercial pathway to increasing countrywide electrification 84

Figure 6.5 – Olowos plaza hourly load demand for a typical weekday, Saturday and Sunday 96

Figure 6.6 – Hourly system operations of the different IPS for a typical weekday 99

Figure 6.7 – Hourly system operations of the different IPS for a typical Saturday 99

Figure 6.8 – Hourly system operations of the different IPS for a typical Sunday 100

Figure 6.9 – Total lifetime cost of all IPS, in descending order of percentage renewable contribution 101

Figure 6.10 – IPS' costs and surplus energy relationship in ascending order of surplus energy generated 102

Figure 6.11 – IPS' costs and GHG emissions relationship in descending order of percentage renewable contribution 105

Figure 7.1 – Creating a sustainable environment through corporate and social responsibility 115

Figure 7.2 – Industrial pathway to increasing countrywide electrification 116

Figure 7.3 – Flowchart of the systematic search implementation on IPS solutions 134

Figure 7.4 – Euler diagram highlighting the benefits of a hybrid photovoltaic-centric power system (HPVPS) option 141

Tables

Table 2.1 – Distribution of Nigerian states into geo-political zones 11

Table 2.2 – Some power sector agencies, their functions and year of establishments 13

Table 2.3 – Some oil and gas sector agencies, their functions and year of establishments 14

Table 2.4 – Nigeria’s SE4ALL targets until 2030 16

Table 2.5 – Nigeria’s energy efficiency targets 17

Table 2.6 – Nigeria’s renewable energy penetration targets 17

Table 2.7– Some RE projects in operation in Nigeria 19

Table 2.8 – Initiatives, Plans and Programmes aimed at improving electrification in Nigeria 21

Table 4.1 – Nigeria’s electricity generation profile 45

Table 4.2 – Distribution companies and their coverage areas 47

Table 4.3 – Cost of electricity to factories in the North-West region 48

Table 4.4 – Cost of electricity to factories in the North-Central region 49

Table 4.5 – Cost of electricity to factories in the North-East region 49

Table 4.6 – Cost of electricity to factories in the South-West region 49

Table 4.7 – Cost of electricity to factories in the South-East region 50

Table 4.8 – Total and average costs of electricity to factories in 2014 and 2015 50

Table 4.9 – Scenario 1 of company X’s cost-benefit analysis of operating a manufacturing plant in Nigeria 51

Table 4.10 – Scenario 2 of company X’s cost-benefit analysis of operating a manufacturing plant in Nigeria 52

Table 4.11 – Scenario 3 of company X’s cost-benefit analysis of operating a manufacturing plant in Nigeria 54

Table 5.1 – Interview on the impact of power supply on business operations in the multi-sectors 68

Table 5.2 – Survey of Abuja city’s residents’ energy usage and renewable energy awareness 73

Table 5.3 – Electricity consumers power system requirements assessed against the performance metrics of affordability, reliability and sustainability 75

Table 6.1 – Summary of the IPS’ system capacities 95

Table 7.1 – Numbers of IPS solutions categorised by their lifetime cost implications 135

Table 7.2 – Numbers of IPS solutions categorised by their yearly GHG emissions (CO_2 tonnes/yr.) 135

Table 7.3 – The 4,950 theoretical IPS solutions categorised by their lifetime cost implications ($/20 years) and yearly GHG emissions (CO_2 tonnes/yr.) 136

Table 7.4 – A breakdown of the Practical IPS solutions and reference systems' capacities against their technical composition, environmental and economic implications 137

Table 7.5 – Optimal IPS solution based on the performance metrics of affordability and sustainability 138

Declaration

This is to certify that the work I am submitting is my own and has not been submitted for another degree, either at University College Cork or elsewhere. All external references and sources are clearly acknowledged and identified within the contents. I have read and understood the regulations of University College Cork concerning plagiarism.

Dedication

This work is dedicated to the Federal Republic of Nigeria (FRN)

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List of Articles, Conferences, Presentations and Publications

Articles

Solar power could stabilise Nigeria's electricity grid and save it money; Published on "The Conversation" [online] available from http://theconversation.com/solar-power-could-stabilise-nigerias-electricity-grid-and-save-it-money-117266 30th May, 2019.

COVID-19: Nigeria should prioritise power supply to health care facilities; Published on "The Conversation" [online] available from http://theconversation.com/covid-19-nigeria-should-prioritise-power-supply-to-health-care-facilities-134444 31st March, 2020.

What Nigeria's poor power supply really costs and how a hybrid system could work for business; Published on "The Conversation" [online] available from https://theconversation.com/what-nigerias-poor-power-supply-really-costs-and-how-a-hybrid-system-could-work-for-business-144609 22nd September, 2020.

Conferences attended

Engineers Ireland – Engineers Policy, Standards and Innovation at Rochestown Park Hotel, Douglas, Cork, Ireland. 21st March, 2017.

8th International Silicon PV Conference on Crystalline Silicon Photovoltaics at Ecole Polytechnique Federale de Lausanne (EPFL), Lausanne, Switzerland. 19th – 22nd March, 2018.

Energy Systems Conference at Queen Elizabeth II Centre, Westminster, London, England. 19th – 20th June, 2018.

Presentations

"Combined effects of dust accumulation and array tilt angle on the energy yield of photovoltaic systems"; Presented at the Energy Systems Conference, London, England. 19th June, 2018.

Publications

Olowosejeje, S., Leahy, P. and Morrison, A.P. (2019). The economic cost of unreliable grid power in Nigeria. *African Journal of Science, Technology, Innovation and Development.* 11 (2), pp. 1 – 11. https://doi.org/10.1080/20421338.2018.1550931 *See Chapter Four*

Olowosejeje, S., Leahy, P. and Morrison, A. P. (2020). A practical approach for increased electrification, lower emissions and lower energy costs in Africa. *Sustainable Futures.* 2, pp. 1 – 10. https://doi.org/10.1016/j.sftr.2020.100022 *See Chapter Six*

Olowosejeje, S., Leahy, P. and Morrison, A. P. (2020). Optimising photovoltaic-centric hybrid power systems for energy autonomy*. Energy Reports*. 7, pp. 1943 – 1953. https://doi.org/10.1016/j.egyr.2021.03.039 *See Chapter Seven*

Abstract

Nigeria's poor electric power supply has grossly affected the economy, slowing down countrywide development. The ever-increasing demand for power supply coupled with its limited availability has been an impediment to her socioeconomic development. The failure to generate and distribute sufficient power has been well documented alongside the inability to realise a lasting solution that wholly addresses the problem. This thesis approached realising a solution by firstly presenting an overview of Nigeria's energy sector in order to identify the barriers to renewable energy uptake. Some of which were high capital costs, lack of access to finance, technical ineptitude, technology paucity, limited public awareness and the lack of government policies or poor policy framework. Thereafter, the analyses of data from the multi-sectors (commercial, industrial, residential and education) realised through interviews and surveys, elicited energy cost savings, energy security and autonomy, improved quality of life, and environmental concern as the motivation for encouraging renewable energy and particularly solar-photovoltaic (PV) uptake. Building on these insights, this body of research presented a case for multi-sectoral adoption of solar-PV as an electricity supply option considering grid power supply unreliability. The technical, economic, environmental and social viability of implementing solar-PV technology were studied by working with country-specific data obtained from surveying the commercial, industrial and residential sectors in Nigeria. These sectors were surveyed to determine the extent of the countrywide power supply unreliability as well as understand the level of public awareness and the societal acceptance of solar-PV as a power generating technology. Cases studied, evidenced the socioeconomic impact of unreliable power supply in Nigeria and a solution to the power supply shortfall is also presented. Numerical simulation and quantitative analysis methods were employed in analysing data and assessing the results. Retrofits to existing petrol/diesel generator systems for the commercial and industrial sectors (C&I) delivered benefits of lower CO_2 emissions, improved systems reliability and reduced grid power dependence at lower lifetime costs than existing power systems. The results from the data analyses suggest that partial to total grid defection solutions that integrate solar-PV technology could be implemented across sectors countrywide, towards improved electrification. Results present a basis for a shift from the power sector electrifying all other sectors to the multi-sectors contributing to the power sector's effort in extending, increasing and improving countrywide electrification. This can be achieved by incentivising the uptake of hybrid photovoltaic-centric power systems (solutions deployed directly where they are needed) as well as taking advantage of the excess power generation from such systems. These solutions would need to be supported by policy and an implementable regulatory framework. This would bring about a measurable improvement in the socioeconomic status of the citizenry and the broader nation.

Keywords: autonomous power producers; climate policy; energy policy; grid defection; hybrid photovoltaic-centric power systems; Nigeria; optimised power systems; socioeconomic development

Glossary of Terms, Abbreviations and Acronyms

Abuja – The capital of Nigeria

Blackout – Sudden and complete interruption of power in a particular service area for hours or days

Beneficial Electrification – Replacing direct fossil fuel use with electricity towards reducing overall emissions and energy costs. *Also referred to as strategic electrification*

Brownout – A deliberate or undeliberate drop in voltage lasting for minutes or hours

BOS – Balance of System

C_{ESS} – energy storage system's lifetime costs ($/20 years)

C_{GS} – generator system's lifetime costs ($/20 years)

$C_{solar\text{-}PV}$ – solar-PV system's lifetime costs ($/20 years)

CAMS – Copernicus Atmospheric Monitoring Service

Captive Power Plant – A power generation plant operated by commercial or industrial energy users for their energy consumption. The plant could be off-grid or grid connected. *Can also be referred to as Auto-producers or Embedded generation*

CBA – Cost Benefit Analysis

CHP – Combined Heat and Power

C&I – Commercial and Industrial

CM – Corrective Maintenance

CO_2 – Carbon Dioxide

Commercial Centre – A complex consisting of more than one semi-structured shopping outlet. *These centres in Nigeria are popularly referred to as shopping plazas or plazas*

Comtridential – A proposed initiative that explores the electrification of the residential sector through excess generation from hybrid renewable energy systems implemented for commercial centres.

DisCos – Distribution Companies

DG – Diesel Generator

DSM – Demand Side Management

$\mathcal{E}_{GS}$: the generator system's yearly GHG emissions (CO_2 tonnes/yr.)

$\mathcal{E}_{IHSBS}$: the integrated hybrid solar-PV and battery based systems' yearly GHG emissions (CO_2 tonnes/yr.)

$\mathcal{E}_{IHSS}$: the integrated hybrid solar-PV based systems' yearly GHG emissions (CO_2 tonnes/yr.)

ECOWAS – Economic Community of West African States

ECREEE – ECOWAS Centre for Renewable Energy and Energy Efficiency

EE – Energy Efficiency

EEI – Energising Economies Initiative

EEP – Energising Education Programme

EPSR – Electric Power Sector Reform

ERGP – Economic Recovery and Growth Plan

ESCO – Energy Service Company

FCT – Federal Capital Territory

FEC – Federal Executive Council

FIT – Feed-in-Tariff

FM – Facility Management

FMP – Federal Ministry of Power (current administration)

FMPWH – Federal Ministry of Power, Works and Housing – added responsibilities/ portfolio (2015 – 2019 administration)

FRN – Federal Republic of Nigeria

GenCos – Generation Companies

Geo-political Zone – The classification of a group of people with similar or shared cultures, ethnicity, history and resources. *There are six geo-political zones in Nigeria: North-Central, North-West, North-East, South-West, South-East and South-South*

GHG – Greenhouse Gas

GIZ – The Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH. *German development agency*

Grid Connected – Electricity supply infrastructure that is connected to the country's main electricity grid network. *Also referred to as grid-tied*

Grid Defection – Electricity supply infrastructure that is not connected to the country's main electricity grid network. *Popularly referred to as off-grid*

GS – Generator System

HPVPS – Hybrid Photovoltaic-centric Power Systems

HRES – Hybrid Renewable Energy Systems

ICREEE – Inter-ministerial Committee on Renewable Energy and Energy Efficiency

IEDN – Independent Electricity Distribution Network

IFFS – Independent Fossil Fuel System

IHGS – Integrated Hybrid Generator-Based System

IHSBS – Integrated Hybrid Solar and Battery-Based System

IHSS – Integrated Hybrid Solar-Based System

In-DisCo – The power infrastructure investment collaboration between Nigerian industries and power distribution companies to guarantee increased power supply access for industries.

IOC – international Oil Company

IPP – Independent Power Producer

IPS – Integrated Power System

IRP – Integrated Resource Planning

JICA – Japan International Cooperation Agency

KEDC – Kano Electricity Distribution Company

kW – Kilowatt

kWh – Kilowatt hour

kWp – Kilowatt Peak

Lagos – The economic capital of Nigeria

LCCA – Life Cycle Cost Analysis

LCOE – Levelised Cost of Energy

MAN – Manufacturers Association of Nigeria

MO – Market Operator

MSME – Micro, Small and Medium Enterprise

MW – Megawatt

MWh – Megawatt hour

MWp – Megawatt Peak

NACOP – National Council on Power

₦ – Naira (Nigeria’s currency)

NCC – National Control Centre

NCDC – Nigeria Centre for Disease Control

NDC – Nationally Determined Contributions

NEEAP – National Energy Efficiency Action Plans

NEM – Net Energy Metering

NEMSA – Nigerian Electricity Management Services Agency

NEP – Nigeria Electrification Project

NEPA – National Electric Power Authority

NEPP – National Electric Power Policy

NESI – Nigerian Electricity Supply Industry

NESP – Nigerian Energy Support Programme

NERC – Nigerian Electricity Regulatory Commission

NNPC – Nigerian National Petroleum Corporation

NPV – Net Present Value

NREAP – National Renewable Energy Action Plans

NREEEP – National Renewable Energy and Energy Efficiency Policy

NWA – Non-Wire Alternatives

Olowos Plaza – A prototypical commercial centre housing commercial outlets

OPEC – Organisation of Petroleum Exporting Countries

PdM – Predictive Maintenance

PG – Petrol Generator

PHCN – Power Holding Company of Nigeria

Pidgin English – An inflected form of the Queen’s English that can be likened to Jamaican creole/patois spoken as a vernacular in Nigeria

PM – Preventive Maintenance

Prosumer – A person who produces a device, product, system or technology for personal consumption

PSRP – Power Sector Recovery Programme

PV – Photovoltaic

PVGIS – Photovoltaic Geographic Information System

RCC – Regional Control Centre

RE – Renewable Energy

REA – Rural Electrification Agency

REB – Rural Electrification Board

REF – Rural Electrification Fund

RES – Renewable Energy System

RESIP – Rural Electrification Strategy and Implementation Plan

RET – Renewable Energy Technology

Reverse In-DisCos – A proposed initiative that supports a role reversal of the traditional In-DisCos, whereby the power distribution companies invest in the modification of their power distribution infrastructure to facilitate the delivery of excess generation from industries to access-deficient regions

RPM – Revolutions per Minute

SAIDI – System Average Interruption Duration Index

SAIFI – System Average Interruption Frequency Index

SE4ALL-AA – Sustainable Energy for All Action Agenda

SES – Solar Energy System

SM – Social Media

SME – Small and Medium Enterprise

SO – System Operator

SON – Standards Organisation of Nigeria

TCN – Transmission Company of Nigeria

TEM – Transactive Electricity Market

TOP – Technical Operating Parameter

ToU – Time-of-Use

TREP – Transmission Rehabilitation and Expansion Programme

TSP – Transmission Service Provider

UniLag – University of Lagos

Wet Stacking – A condition in diesel engines where the unburned fuel passes on to the exhaust system. *It could truncate electric power generators service life if left unchecked*

Yoruba – One of the three major languages in Nigeria. *The others are Hausa and Igbo*

CHAPTER ONE

Introduction

1.1. Research background

"NEPA has taken light"; "Up NEPA"

– Statements made in most Nigerian households when there is a power outage and when there is a restoration of power supply

Throughout my childhood in Nigeria, my quality of life was affected by the unreliability of power supply, as I had to study under the candle light and sometimes with the aid of kerosene lanterns. I also missed out on watching cartoons, playing video games and had to sleep in the heat, especially at night times when its effect could not be consciously ameliorated. Two decades later and Nigeria is still beleaguered by electricity unreliability and intermittency. It is quite befuddling that the country can boast of the largest economy [10] and richest man in Africa [11], yet still have over 62% of its population living in abject poverty [10].

Energy unavailability and inaccessibility inhibits the socioeconomic development of any country. Countries over the years have relied on the use of natural gas and other fossil fuels such as; oil, coal, etc., in generating and securing their power supply access. These energy sources, proven to emit greenhouse gases (GHGs), [1] have been widely documented to effect unfavourable climate change [2] [3].

In mitigating the effect of conventional power generation on the environment, renewable energy (RE) sources such as; the sun, wind and water; are being harnessed for power generation. In fostering equitable and sustainable development, countries with RE sources, human capital and an enabling policy, supported by effectual regulatory frameworks, are integrating RE technologies (RETs) and infrastructure in the continued development and expansion of their power systems [4].

Nigeria, although blessed with some of these renewable resources (water, sunlight, and vegetative land), is still heavily reliant on fossil fuels for its power generation with 84% of generation attributed to gas-fired power plants [5]. The three large hydro-power plants in the country (Kainji Dam in Niger State, Jebba Dam in Kwara State and Shiroro Dam also in Niger State) form the remaining 16% of the country's electricity mix [5]. Since their development in the 1960's up until the 1990's [5], no other large scale grid-tied RE project has been commissioned, thus stagnating the capacity share of RE in the country's electricity mix [5].

Despite the availability of both conventional and non-conventional power generation sources, the country still experiences regular power outage with some rural communities underserved – unserved by grid power supply [8]. In light of these, it is necessary that electric power supply is stable and eventually uninterrupted for economic growth, development, and improvements to the livelihood of the citizenry. Furthermore, it is important the environment is considered when exploring power generating solutions that can augment available generation capacity.

1.1.1. Problem statement

Nigeria's vision 20:2020 (becoming one of the top 20 economies in the world by 2020) was not realised due to its electricity paucity (hovering around 3,000 – 5,000 MW) [6], amongst other factors. Nonetheless, countrywide energy sufficiency is still considered critical in diversifying its economy and meeting the energy demand of a growing population [7]. It is therefore important that policies and regulatory frameworks are structured to accelerate efforts that wholly addresses countrywide electricity availability and accessibility towards driving economic, social and environmental sustainable development.

1.1.2. Research objectives

This thesis's research objectives are:

- Raising technical awareness on Nigeria's electricity situation by undertaking studies guided by the pillars of economic, social and environmental performance;
- Proposing practical solutions to increasing and sustaining Nigeria's electric power supply availability and accessibility with focus on driving economic, social and environmental sustainable development;
- Using photovoltaic (PV) resource data and demand profiles to simulate a large suite of potential solar-PV-Diesel Generator (DG) hybrid solutions and select the best-performing from economic, environmental perspectives, while satisfying user requirements;
- Exploring the application of such solutions given Nigeria's resource base (natural resource i.e. abundant sunlight) and economic potential;
- Concluding with proposals for change that have an analytical basis.

1.2. Research approach

A mixed method [9] was adopted in realising the research objectives. The method comprised of qualitative and quantitative analyses. These analyses followed from garnering theoretical understanding of the problem presented and solutions available. The qualitative part employed the use of case studies and questionnaires in establishing focal study areas and collecting data from same. The quantitative part focussed on converting textual data to numeric data. Subsequently, mathematical calculations and numerical simulation were employed in the data analysis. The broader research approach is broken into two parts: the philosophical worldview (pre-method selection) and the research design (post-method selection) [9].

1.2.1. Philosophical worldview

This philosophical worldview is centred on viewpoints and reasoning. It informed the methods by understanding the research objectives and the best way to realise them. The pragmatic worldview embodied this thesis's viewpoints, most especially on this research. Its major reasoning elements are [9]: consequences of actions, problem-centred, pluralistic and real-world practice oriented. As such, it is the basis of a mixed method [9].

1.2.2. Exploratory sequential mixed method

A design (exploratory sequential mixed method) [9] that epitomized the research approach was selected. The research design guided the implementation of the method by giving direction on the procedures to follow. The sequence involved exploring the focal study areas primarily through the use of questionnaires (qualitative phase) for data gathering and collection. This was succeeded by the data analysis (quantitative phase) which elicited findings integral to the theoretical and practical contribution of this work.

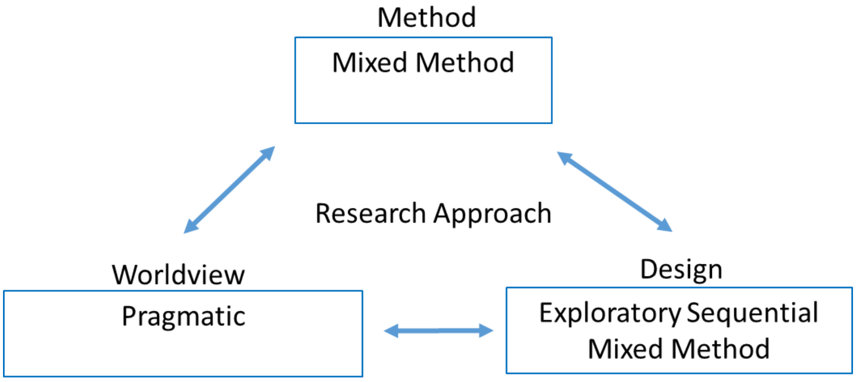


Figure 1.1 – Framework of the research approach – Adapted [9]

1.3. Expected contribution

This work envisages contributing theoretically and practically to the research domain of energy in Nigeria, particularly to the power sector through:

- Adding to the repository/knowledge pool on Nigeria’s electricity paucity and the exploration of non-conventional power solutions;
- Consolidating the application of optimization techniques in power systems analysis;
- Arguing for grid defection by presenting a case on commercial centres built around their power infrastructure;
- Making a case for further deregulation of Nigeria’s electricity sector to accommodate more power producers towards reduced electricity costs and the sustainable electrification of the multi-sectors that contribute to its economy;
- Presenting the functional expansion of Nigeria’s electricity mix (through the uptake of solar-photovoltaic (PV) technology) as a significant factor in advancing the country’s socioeconomic development through improved electrification;
- Informing climate policy formulation on greenhouse gas (GHG) emissions reduction by presenting the viability of the multi-sectoral adoption of grid defection solutions that primarily employ the use of low-carbon power technology (solar-PV).
- Informing energy policy formulation by presenting electrification pathways that addresses the non-electrification of unserved communities, the partial electrification of underserved communities and the intermittent electrification of served communities.

“Àbá ní ńdi òtító; ojo ni kì íjé ká” (Yoruba Proverb)
– Nothing is accomplished without striving

1.4. Research structure

The chapters are structured as follows:

Chapter Two sheds light on Nigeria's energy sector with further insight on the country's electricity subsector. The RE subsector is brought under focus by establishing its state of affairs. Key aspects that underpin the subsector's performance: the resource availability, RE deployment rates and limitations in the Nigerian context are reviewed. The multi-sectoral CO_2 emission rates are established, with particularity on estimating the energy sector's contribution to countrywide GHG emissions. Areas for a potential research contribution highlighted during the overview helped in formulating the research questions.

Chapter Three describes the methods selected and how their implementation aided the research. Defining the case studies presented on the commercial and industrial sectors (C&I) were fundamental in outlining a research pathway. Subsequently, other methods such as; qualitative analysis, quantitative analysis, and numerical simulation were employed in analysing raw data obtained through questionnaires and surveys. In the first case studied, a cost-benefit analysis was carried out on the data supplied by industries. The survey of commercial centres' activities and the power system solutions inferred in the first case study, informed the integrated power systems' (IPS) systematic design analysis in the second case study that was guided by the three fundamental pillars of: affordability, reliability and sustainability. A wider power system solutions search space (wider than the one considered in the second case study) was further explored using numerical simulation in realising an optimal power systems solution for the C&I sectors. Questionnaires assisted in providing mainly textual data that transitioned to surveys when analysed. The chapter also justifies the selected methods used for analysis within this research.

Chapter Four introduces the primary case study of the research. It elicits the problem of electricity supply countrywide by presenting a case study on the industrial sector. A cost-benefit analysis is carried out on the data realised through a survey of Nigerian industries. The findings of the analysis were highlighted in the salient points. The chapter concludes by putting into perspective the economic impact of Nigeria’s electricity paucity, therefore creating a theme for subsequent chapters to follow.

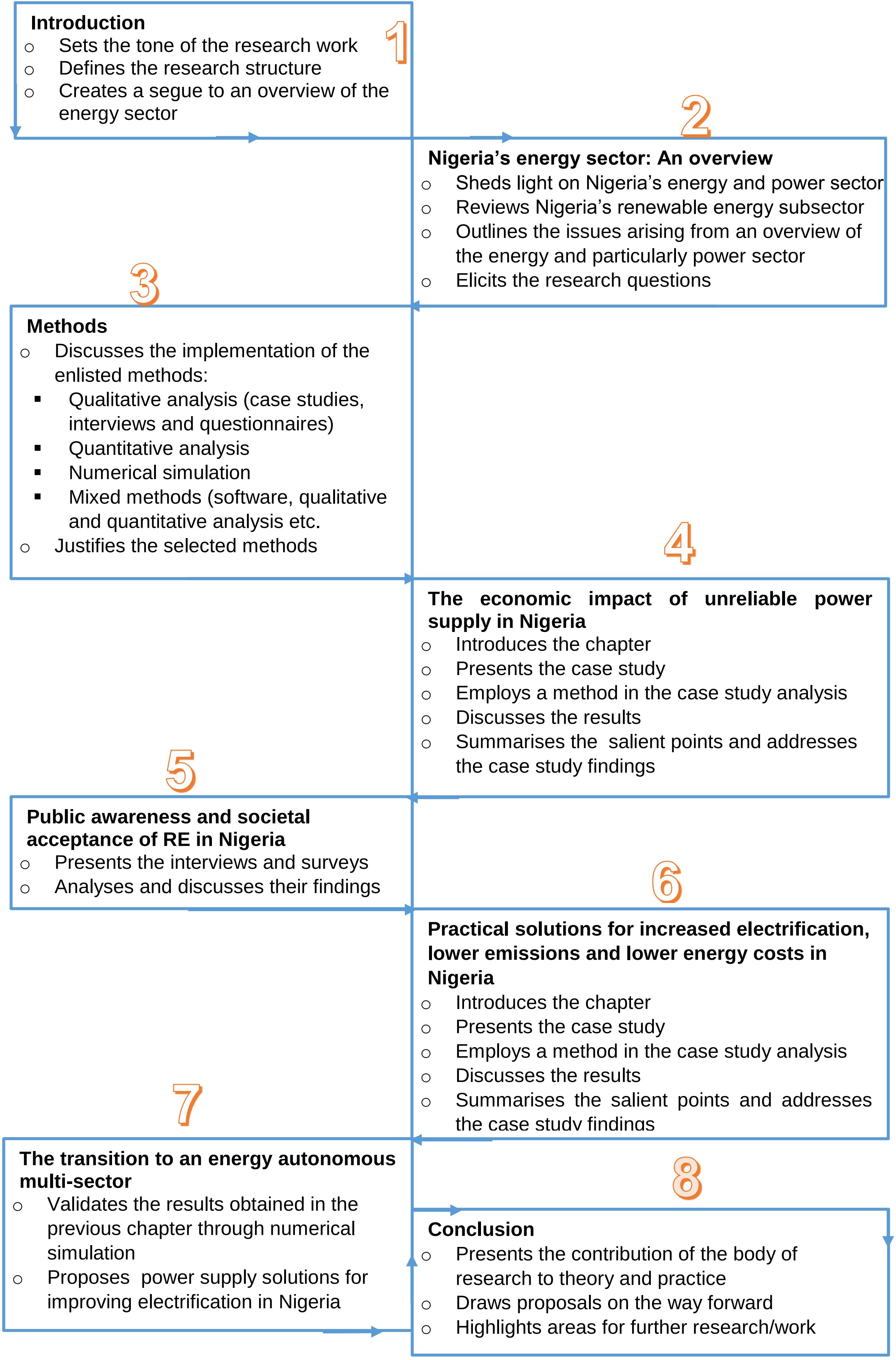
Chapter Five presents a social study on Nigeria’s populace with emphasis on determining the societal acceptance and public awareness of RE in Nigeria. Interviews are initially conducted to determine the impact of unreliable power supply to business operations and quality of life. Thereafter, an analysis to extract workable data for the study is carried out on the questionnaires electronically distributed to the public. Discussions are centred on the general perception of RETs and their openness to alternative energy sources. The conclusion covers the impact of unreliable power supply to businesses and the peoples’ viewpoint on the most suitable RET for implementation in Nigeria. This chapter also forms the intermediary between the primary case study and the focal case study.

Chapter Six introduces the focal case study of the research. It presents a solution to the power supply intermittency in the commercial and industrial (C&I) sectors by undertaking a case study on the commercial sector. The systematic analysis on the IPS solutions considered are assessed against three impact metrics. The solutions in the feasible space are further analysed in realising a single optimal solution. Discussions contextualise the application of the realised solutions and the extent to which they can be effectual. Conclusions present the salient points of the case study (benefits of implementing these solutions to the economy, on the quality of life, to the environment and most of all, in informing energy policy).

Chapter Seven employs the use of numerical simulation in validating the power system solutions realised in the previous chapter. It elicits the economic viability of environmentally optimised power system solutions. It also presents other electrification pathways and highlights the importance of policy actions in realising them.

Chapter Eight concludes by discussing the contribution of the research both to theory and practice. It also reports on the implications of the research approach. The chapter and the thesis concludes with recommendations and suggestions on areas for further research.

1.5. Conceptual framework



Introduction

- Sets the tone of the research work
- Defines the research structure
- Creates a segue to an overview of the energy sector

Nigeria's energy sector: An overview

- Sheds light on Nigeria's energy and power sector
- Reviews Nigeria's renewable energy subsector
- Outlines the issues arising from an overview of the energy and particularly power sector
- Elicits the research questions

Methods

- Discusses the implementation of the enlisted methods:
  - Qualitative analysis (case studies, interviews and questionnaires)
  - Quantitative analysis
  - Numerical simulation
  - Mixed methods (software, qualitative and quantitative analysis etc.
- Justifies the selected methods

The economic impact of unreliable power supply in Nigeria

- Introduces the chapter
- Presents the case study
- Employs a method in the case study analysis
- Discusses the results
- Summarises the salient points and addresses the case study findings

Public awareness and societal acceptance of RE in Nigeria

- Presents the interviews and surveys
- Analyses and discusses their findings

Practical solutions for increased electrification, lower emissions and lower energy costs in Nigeria

- Introduces the chapter
- Presents the case study
- Employs a method in the case study analysis
- Discusses the results
- Summarises the salient points and addresses the case study findings

The transition to an energy autonomous multi-sector

- Validates the results obtained in the previous chapter through numerical simulation
- Proposes power supply solutions for improving electrification in Nigeria

Conclusion

- Presents the contribution of the body of research to theory and practice
- Draws proposals on the way forward
- Highlights areas for further research/work

Figure 1.2 – Conceptual framework of the research

CHAPTER TWO

Nigeria’s energy sector: An overview

2.1. Background on Nigeria

Nigeria is the most populous country in Africa with an estimated population of 185,359,924 people [7]. Nigeria is also listed as the seventh most populous nation in the world, with urban and rural population distribution at 48.1% and 51.9% respectively [7]. The Country, a former colony of the United Kingdom, gained her independence on 1st October, 1960 and later became a republic i.e. Federal Republic of Nigeria, in 1963 [28]. Nigeria borders Niger to the North, Benin Republic to the West, Chad and Cameroon to the East. This is shown in Figure 2.1.

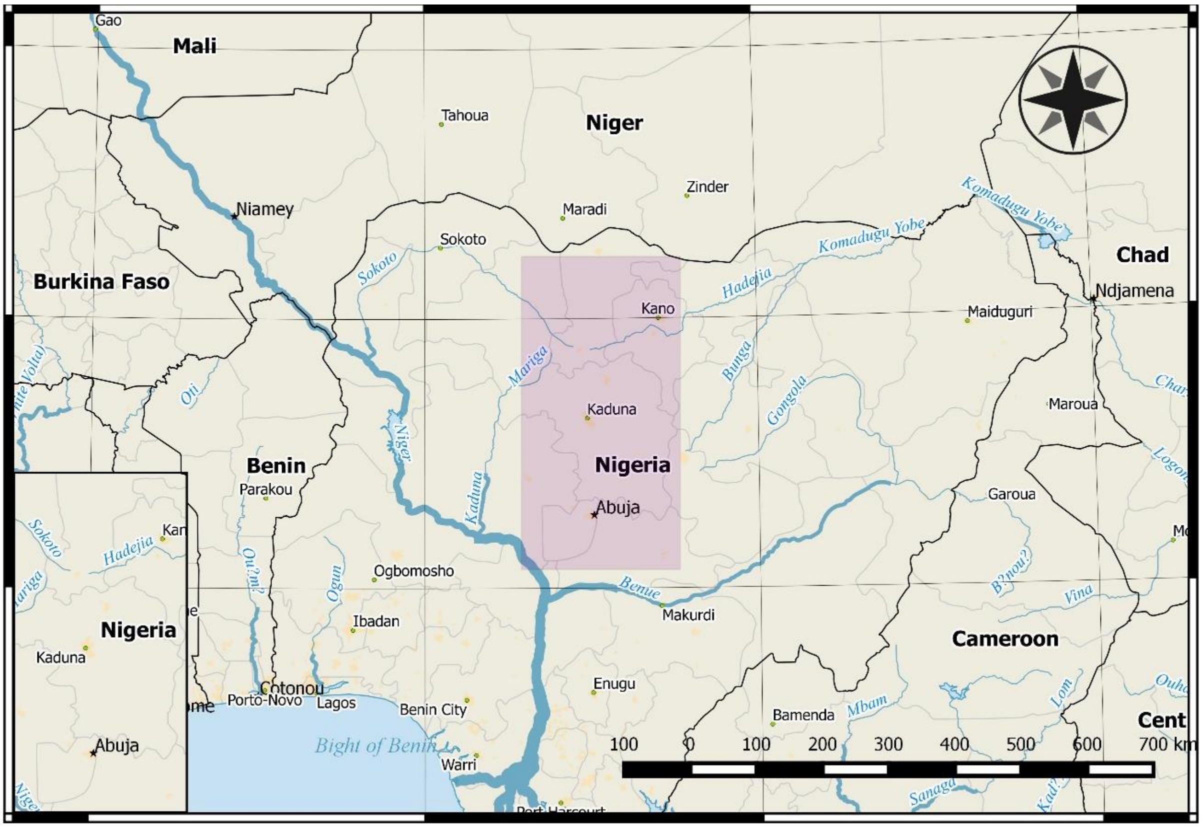


Figure 2.1 - Map of Nigeria showing its land borders and the Federal Capital Territory (Abuja)

For ease of governance and political stability, Nigeria is divided into six geo-political zones comprising 36 states and the Federal Capital Territory (F.C.T.). Each state is governed by a governor, except the F.C.T., which is headed by a cabinet minister. Table 2.1 shows the states distribution into geo-political zones with their corresponding capital cities.

Table 2.1 – Distribution of Nigerian states into geo-political zones

Geo-political Zone	States (Capital)	Number of States
North-Central	F.C.T-Abuja, Kogi (Lokoja), Benue (Makurdi), Kwara (Ilorin), Nasarawa (Lafia), Niger (Minna), Plateau (Jos)	7
North-West	Jigawa (Dutse), Kaduna (Kaduna), Kano (Kano), Katsina (Katsina), Kebbi (Birnin-Kebbi), Sokoto (Sokoto), Zamfara (Gusau)	7
North-East	Borno (Maiduguri), Yobe (Damaturu), Taraba (Jalingo), Gombe (Gombe), Adamawa (Yola), Bauchi (Bauchi)	6
South-West	Lagos (Ikeja), Ogun (Abeokuta), Oyo (Ibadan), Osun (Osogbo), Ondo (Akure), Ekiti (Ado-Ekiti)	6
South-East	Enugu (Enugu), Abia (Umuahia), Anambra (Awka), Imo (Owerri), Ebonyi (Abakaliki)	5
South-South	Rivers (Port-Harcourt), Akwa Ibom (Uyo), Delta (Asaba), Cross-River (Calabar), Edo (Benin City), Bayelsa (Yenegoa)	6

2.1.1. Climate and weather

Nigeria's climate is tropical with two seasons annually. The wet season occurs from April to October with lower monthly temperatures and the wettest month being June [29], while the dry season starts from November and lasts till March, with temperatures rising above 38ºC during the day and falling as low as 12ºC at night. The dry season brings about the dry, dusty and reddish harmattan winds from the Sahara that sweeps across the north eastern region of the country whilst the south western winds bring about cloudy and rainy weather [29].

2.1.2. Economic situation

Nigeria's gross domestic product (GDP) was rebased in 2013, and revised upwards to approximately $500 billion, thus making it the largest economy in Africa [8]. The top five drivers of the economy, cumulatively representing more than 70% of her GDP are the Agricultural, Trade (goods and services), Oil & Gas, Information & Communication and the Manufacturing sectors [8]. Nigeria's top revenue earner remains the Oil & Gas sector, with export earnings of $3.69 billion for the period January – September, 2015 [30]. Despite this, Nigeria's unemployment rate was recorded at 23.10% for the 3rd quarter of 2018 [31] with inflation running at 12.13% as of January 2020 [17].

2.1.3. Population density and regional distribution

States with job opportunities, basic access to social amenities, better road networks, and modern infrastructure amongst other factors, have experienced a higher influx of people in recent years. Lagos (the commercial capital of Nigeria) in particular, is experiencing a population explosion attributable to these aforementioned factors. Figure 2.2 shows Nigeria’s population density per state.

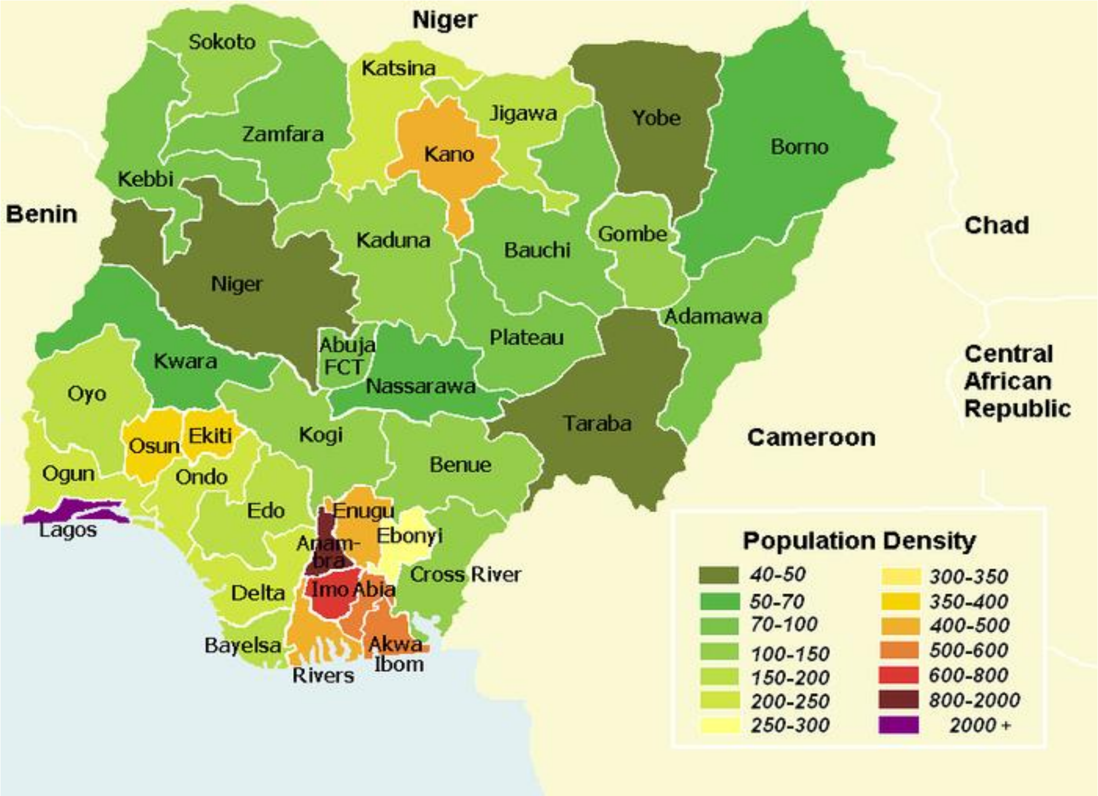


Figure 2.2 - Map of Nigeria showing population density of persons per km^2 [32]

2.2. Nigeria’s power sector

Between the 1980s and 1990s, the Nigerian government did not invest sufficiently in its electricity infrastructure, thereby ensuring that electricity production didn’t keep pace with the ever growing Nigerian population. The sector was characterised by management inefficiencies, little to zero maintenance on existing infrastructure, lack of grid infrastructure expansion, amongst others [5]. This resulted in dwindling power generation levels, frequent transmission systems collapse and technical losses leading to a reduction in power supplied to consumers. Up to one third of the power generated by the Nigerian Electric Power Authority (NEPA), was lost in transmission to the end users [5]. The wholly owned government entity NEPA was underperforming and had no incentive to deliver consumer value, as it operated in an entirely monopolistic market.

The promulgation of the Electricity Power Sector Reform (EPSR) Act in 2005, led to the unbundling of NEPA into eighteen "successor" companies i.e. six generation companies (GenCos), one transmission company (Transmission Company of Nigeria) and eleven distribution companies (DisCos). These companies remained under a holding company – Power Holding Company of Nigeria, (PHCN) until September 2013 when they were conceded and subsequently handed over to investors (November, 2013) in line with the power sector reform objectives [5]. As a consequence of the privatisation of the power sector, integral government agencies were established to facilitate the seamless implementation of the EPSR Act's core objectives throughout the reform process. Some of these agencies, their functions and years of establishment are listed in Table 2.2. The Federal Ministry of Power at the apex of the power sector's organogram, drives the sector's policy guided by the EPSR act, the National Electric Power Policy (NEPP) of 2001 and the roadmap of power sector reform of 2010 [118].

Table 2.2 – Some power sector agencies, their functions and years of establishment - Adapted [5]

Agency	Functions	Year of Establishment
Nigerian Electricity Regulatory Commission (NERC)	Issuance of licenses and establishment of rules for industry regulation	2005
Niger Delta Power Holding Company Limited (NDPHC)	Execution of the National Integrated Power Project (NIPP) with intent to divest the generation assets and transfer the mid and downstream assets to the respective operating entities	2005
Rural Electrification Agency (REA)	Management of off-grid power solutions	2006
Nigerian Electricity Liability Management Company Limited (NELMCO)	Management of liabilities of Power Holding Company of Nigeria	2006
Nigerian Bulk Electricity Trading PLC (NBET)	Single government backed off-taker and electricity trader	2010
Presidential Task Force on Power (PTFP)	Implementation driver of the Nigerian power sector reforms	2010 ***(Dissolved in 2016)***
Nigerian Electricity Management Services Agency (NEMSA)	Enforcement of technical regulations in the Nigerian Electricity Supply Industry (NESI)	2013

2.2.1. Oil and gas subsector

Crude oil was first discovered in 1956 in Oloibiri, Niger-Delta region of Nigeria [113]. Twenty-one years later (1977), the Nigerian National Petroleum Corporation (NNPC) – a federal government parastatal, was established to undertake commercial ventures in the petroleum industry [113]. Over the years, the oil and gas sector has consolidated its position as Nigeria's biggest revenue earner with earnings of ₦ 5.39 trillion and ₦ 5.54 trillion in 2018 and 2019 (fiscal years) respectively [114]. The Federal Ministry of Petroleum Resources through its parastatals regulates the upstream, midstream and downstream activities of Nigeria's oil and gas sector. Some of these agencies, their functions and years of establishment are listed in Table 2.3.

Table 2.3 – Some oil and gas sector agencies, their functions and years of establishment [116]

Agency	Functions	Year of Establishment
Department of Petroleum Resources (DPR)	Technical department of the ministry that regulates and monitors activities of the oil and gas industry	1985
Petroleum Training Institute (PTI)	Engaged in the development of human capital for Nigeria's petroleum industry	1973
Petroleum Technology Development Fund (PTDF)	Saddled with the responsibility of educating and training Nigerians in (for) the petroleum industry	1973
Petroleum Equalisation Fund (PEF)	Saddled with overseeing petroleum bridging activities. Responsibilities of reimbursing marketers the cost of transporting white petroleum products from supply points to retail outlets	1975
Nigeria Nuclear Regulatory Authority (NNRA)	Is responsible for regulating and monitoring all activities involving the development and use of nuclear radioactive materials in the country.	1995
Petroleum Product Price Regulatory Agency (PPPRA)	Responsible for fixing the benchmark prices of petroleum products as well as regulating and monitoring the transportation and distribution of petroleum products in Nigeria	2003
Nigerian Content Development and Monitoring Board (NCDMB)	Vested with the responsibility of implementing local content in the oil and gas industry	2010

According to the Organisation of Petroleum Exporting Countries (OPEC), as at the end of 2018, Nigeria's proven crude oil reserves were set at 36.97 billion barrels [115]. Despite these figures, derelict petroleum refineries have resulted in the importation of refined hydrocarbons to meet domestic demand [113]. The inadequacy of Nigeria's oil and gas sector has implications on its economic growth and development. A fragmented gas market [88] impacts the performance of the electric power supply value chain, particularly at the generation apex, as 84% of power generation is attributed to gas-fired power plants [5]. Also, extended hours spent in queues at gas stations during nationwide fuel scarcities aggregates to productive man-hours lost as a result of sectoral deficiencies [117].

2.2.2. Renewable energy subsector

In April 2015, the Federal Executive Council (FEC) approved the National Renewable Energy and Energy Efficiency Policy (NREEEP) [34]. The NREEEP document addresses key areas such as; renewable energy supply & utilisation, renewable energy pricing and financing; legislation; regulation and standards; energy efficiency and conservation; renewable energy project implementation issues; research and development; capacity building and training; gender and environmental issues and planning and policy implementation [34]. In summary, the policy's thrust is the optimal utilisation of Nigeria's energy resources for sustainable development.

As the NREEEP directs the Minister of Power to develop the National Energy Efficiency Action Plan (NEEAP) and the National Renewable Energy Action Plan (NREAP) within 6 – 12 months of approval of the NREEE [123 – 124], the NEEAP (2015 – 2030) and NREAP (2015 – 2030) were approved alongside the national Sustainable Energy For All Action Agenda (SE4ALL-AA) in July, 2016, by the National Council on Power (NACOP) [123 – 125].

The Rural Electrification Strategy and Implementation Plan (RESIP) prepared by the Federal Ministry of Power, Works and Housing (FMPWH) for implementation by the Rural Electrification Agency (REA) was also approved in July, 2016. In 2012, Nigeria outlined its country-level SE4ALL effort towards realising the United Nations' SEforALL global initiative by 2030 [125]. The country has been able to tie in its national effort into sub-regional (member states of ECOWAS) efforts being co-ordinated by the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE) [125]. Nigeria's SE4ALL objectives are quantified in Table 2.4.

Table 2.4 – Nigeria's SE4ALL targets until 2030 [125]

Focus	Targets until 2030
Energy Access	• To increase electricity access from the current aggregate level of 40% (urban = 65% and rural = 28%) in 2015 to 75% (urban = 90% and rural = 60%) by 2020 • By 2030, the population share living without electricity supplies will drop from the 60% in 2015 of the total population down to about 10% • To replace 50% of traditional firewood consumption for cooking by improved cook stove technology by 2020 and 80% by 2030 • Working together with the private sector to roll-out LPG at affordable cost for Nigerians by 2020 and subsequently up to 2030 • By 2025 and 2030, nuclear energy is expected to contribute about 2.5% and 4% to available electricity mix • The electricity generation will increase from the present grid supply of 5,000 MW in 2015 to at least 32,000 MW in 2030
Energy Efficiency	• By the end of 2015, efficient lighting will be used by 20% of the households, 40% by 2020 and almost 100% by 2030 • For high-energy consuming sectors (transport, power and industrial sectors), efficient energy technologies will be progressively introduced as well as other demand side management measures such as; peak load management when possible. Compared with 2015 level, energy efficiency will increase by at least 20% by 2020 and 50% by 2030 • By 2016, energy audits will be compulsory for all high-energy consuming sectors and public buildings
Renewable Energy	• Nigeria's electricity vision 30:30:30 is to achieve a technology-driven renewable energy sector that harnesses the nation's resources to complement its fossil fuel consumption and guarantees energy security. Specifically, Nigeria's target for renewable energy is: • By 2030, renewable energy is expected to contribute at least 30% share in the available electricity mix; • To achieve a 27% and 20% contribution of hydroelectricity (both large and small hydro) to the nation's electricity generation mix by 2020 and 2030 respectively; • To achieve a 2.5% contribution of wind energy to the nation's electricity generation mix by 2030; • To achieve a 20% and 19% contribution of solar energy (PV and solar thermal) to the nation's electricity generation mix by 2020 and 2030 respectively; • To achieve and maintain a 4% power generation capacity using biomass resource by 2020 and 2030 • Achieve 10% biofuel blend by 2020 using locally produced bio-fuel from secondary biomass.

The NEEAP (2015 – 2030) is premised on espousing the effective and efficient use of energy for critical sectors/areas like the residential, transportation, services/C&I, agriculture and the built environment [123]. The national energy efficiency targets are highlighted in Table 2.5.

Table 2.5 – National energy efficiency targets [123]

Period	Targets
2020	• Efficient lighting will be used by 40% of households • For high-energy consuming sectors (transport, power and industrial sectors) efficient energy will increase by at least 20% compared to baseline • Achieve 10% biofuels blends • Improve the efficiency of the bioenergy sector • Distribution loss reduction target up to 15 – 20%
2030	• Efficient lighting will be used by almost 100% of households • For high-energy consuming sectors (transport, power and industrial sectors) efficient energy will increase by at least 50% compared to baseline • Curb firewood demand below supply capacity • Distribution loss reduction target to less than 10%

The NREAP (2015 – 2030) outlines the federal government effort towards realising the objectives of its renewable energy policy. These include – security of supply, climate protection, business competitiveness, promotion of technology and innovation and also securing electricity access to its populace [124]. The NREAP targets are covered in Table 2.6.

Table 2.6 – Nigeria's renewable energy penetration targets [124]

Focus	**Targets (time frame)**		
Grid-connected RE			
In MW installed capacity	**2010**	**2020**	**2030**
Renewable energy installed capacity in MW (including large and medium scale hydro)	916	5,325	13,800
Renewable energy share of the total installed capacity in % (including medium and large hydro)	21	52	43
Grid-connected generation (GWh)	**2010**	**2020**	**2030**
Total renewable energy generation in GWh (including medium and large hydro)	4,749	20,031	49,766
Renewable energy share in the electricity mix in % (including medium and large hydro)	17	38	29
Off-grid applications	**2010**	**2020**	**2030**
Share of rural population served with off-grid (mini-grids and stand-alone) renewable energy electricity services in %	1.2	25	40
Domestic cooking energy	**2010**	**2020**	**2030**
Share of population using improved cook stoves in %	0.24	40	59
Share of charcoal produced by efficient charcoal production technologies in %	2	5	7
Use of modern fuel alternatives for cooking (e.g. LPG, biogas, solar cookers, ethanol gel fuel, etc.) - % of population	97.7	55	34
Solar water heaters	**2010**	**2020**	**2030**
Number of residential houses with solar thermal systems in %	0	5	7
Share of district heath centres, maternities, school kitchens and boarding schools with solar thermal systems in %	0	0.5	5
Share of agro-food industries (preheating of process water) with solar thermal systems in %	0	2	5
Share of hotels with solar thermal systems in %	0	5	10
Biofuels	**2010**	**2020**	**2030**
Ethanol as a share of gasoline consumption	8.5	33.2	57.3
Biodiesel as a share of Diesel and Fuel oil consumption	1.8	6.2	17.5

The RESIP objectives [126] are to:

i. Promote agriculture, industrial, commercial, economic and social activities in rural areas;
ii. Raise the living standards of rural population through improved water supply, lighting and security;
iii. Promote the use of domestic electrical appliances to reduce the drudgery of household tasks typically allocated to women;
iv. Promote cheaper, conventional and more environmentally friendly alternatives to the prevalent kerosene, candle and vegetable oil lamps and fossil fuel powered generating sets;
v. Assist in reducing migration from rural to urban areas; and
vi. Protect the nation's health and environment by reducing indoor pollution and other energy related environmental problems

Objectives i, ii, iv and vi closely align with the focus of this thesis

2.2.2.1. Renewable energy resource availability

Hydropower: According to the NREEEP document [34], Nigeria has a large scale hydropower potential of approximately 10,000 MW and small/medium scale potential upwards of 3,500 MW.

Biomass: The country's biomass resources include wood fuels and by-products from crops such as; forage grasses, shrubs, rice husks [34]. They also include animal wastes and wastes from multi-sectoral (forestry, agricultural and industrial) activities such as; saw-dust and aquatic biomass [34].

Solar: The annual average of total solar radiation in the country varies from about 12.6 MJm^{-2} per day in the coastal regions and about 25.2 MJm^{-2} per day in the northern region [34].

Wind: The annual average wind speed at 10 m height varies from about 2 ms^{-1} in the coastal regions to about 4 ms^{-1} in the most northern regions of the country [34]. At 50 m height, it ranges from 2 ms^{-1} to 8 ms^{-1} [34].

Geothermal, Wave and Tidal: Research is still required to quantify a countrywide resource base and power generating potential [34].

2.2.2.2. Renewable energy deployment rates

Hydropower: 15% of the 10,000 MW large hydropower potential capacity has been developed as at 2012 [34]. Only 2% of the country's small and medium scale hydropower potential capacity estimated at 3,500 MW has been tapped as at 2012 [34].

Biomass: There's a paucity of information on its country-level scale of deployment.

Solar: Some off-grid electrification projects driven by the REA are ongoing and have been commissioned since the NREEEP was approved. Notably are the Sura shopping complex [110] commissioned in 2018 and the ongoing off-grid power development project for the University of Lagos (UniLag) [111].

Wind: There are conflicting reports on the status of a 10 MW wind energy project commenced in 2010 in Katsina state [5] still to be commissioned.

Some of the public and private RE completed projects in recent years are highlighted in Table 2.7.

Table 2.7 – Some RE projects in operation in Nigeria [127-129]

RE Technology (RET)	Project	Project Developer/ Implementing Body	Year Commissioned
Solar-PV-Diesel hybrid	12.6 kW off-grid residential building (10 apartments) in an estate in Guzape, Abuja	Blue Camel Energy	2014
Solar-PV-Diesel hybrid	1.2 MW power system project for F.C.T water board in Bwari, Abuja.	Japan International Cooperation Agency (JICA) – through its contractors	2016
Solar-PV-Diesel hybrid	2.8 MW power system for Alex Ekueme Federal University, Ebonyi state	REA – with support from the World Bank and African Development Bank	2019
Solar-PV-Diesel hybrid mini-grid	64 kW solar hybrid system (with 60 kWh battery storage) for Rokota community in Niger state	REA – with support from the World Bank and African Development Bank	2019
Solar-PV-Diesel hybrid mini-grid	100 kW designed to serve 350 residential buildings, 90 commercial buildings and 5,500 people in Akpabom community in Akwa-Ibom state	REA – with support from the World Bank and African Development Bank	2019
Solar-PV-Diesel hybrid	25 kW power system for the Nigeria Centre for Disease Control's (NCDC) public health laboratory, Abuja	Blue Camel Energy/REA	2020
Solar-PV-Diesel hybrid	10 kW and 20 kW for two isolation centres in Ogun state	REA	2020

2.2.2.3. Renewable energy deployment limitations

Going by Table 2.7, the approval of RESIP has empowered the REA to implement off-grid RE solutions for the rural deficient and contributing sectors (e.g. commercial) to the economy. Nonetheless, some factors still limit the uptake of RE in Nigeria. They are:

- Policy development and implementation – In a case where there is adequate policy, the regulatory infrastructure and means of enforcement could still present a problem;
- Technical ineptitude – due to the state and quality of education in the country [130]. It also extends to the state and quality of specialised training i.e. vocational training and apprenticeship [130];
- Technology poverty – due to power supply unreliability, technical ineptitude and importation costs and duties;
- Lack of public awareness – due to low levels of RE projects i.e. RE development projects that are running the course of their lifetimes. Most of the new RE projects implemented have been in operation for less than 10 years (see Table 2.7). There is also a lack of mainstream awareness programmes on the benefits of RE, possibly due to low levels of baseline RE projects that can be used as reference points;
- Lack of access to finance – due to reasons covered in the previous bullet point. Financial institutions consider RET projects a high risk investment i.e. not as mature and bankable as fossil fuel alternatives;
- High capital costs – due to a lack of access to finance, technical ineptitude [130], paucity of technology resulting in importation of constituent devices and technologies as well as policy actions i.e. imposition of 10% tax duty on solar modules [104].

2.2.2.4. Energy use in Nigeria

The International Energy Agency (IEA) [154] estimated Nigeria’s total energy use at 1,638.7 TWh in 2018, with biofuels and waste contributing 1,286.44 TWh, oil products (280.56 TWh), natural gas (40.52 TWh), electricity (30.84 TWh i.e. 200 kWh/capita) and coal (0.34 TWh).

2.3. Initiatives, Plans and Programmes aimed at improving electrification in Nigeria

Some of the initiatives, plans and programmes aimed at improving electrification in Nigeria that have been rolled out in recent years are summarised in Table 2.8**.**

Table 2.8 – Initiatives, Plans and Programmes aimed at improving electrification in Nigeria

Initiative, Plans and Programmes	Responsible Body	Objectives [110, 111 and 133 – 135]	Launch
Economic Recovery and Growth Plan (ERGP)	Presidency	To restore economic growth through structural reforms	2017
Power Sector Recovery Programme (PSRP)	Presidency	• To restore the power sector's financial viability, improve power supply reliability; • To strengthen the sector's institutional framework; • To increase transparency; • To implement policies that promote and encourage investor confidence; • To institutionalise a contract-based electricity market	2017
Nigeria Electrification project (NEP)	REA	• To increase electricity access to households, micro, small and medium enterprises (MSMEs); • To provide clean, safe, reliable and affordable electricity through RE sources to unserved and underserved communities; • To develop a data driven off-grid model for Nigeria that will become an exemplar for sub-Saharan Africa; • To provide reliable power supply for 250,000 MSMEs and 1 million households	2017
Energising Economies Initiatives (EEI)	REA	To rapidly deploy off-grid energy solutions to sectors that drive economic activities like agricultural, commercial and industrial	2017
Energising Education Programme (EEP)	REA	• To provide off-grid energy solutions to 37 federal universities and 7 university teaching hospitals; • To develop a RE teaching centre in each of the universities	2017
Transmission Rehabilitation and Expansion Programme (TREP)	Transmission Company of Nigeria (TCN)	• To expand the national grid's capacity and coverage areas; • To establish an effective and well-motivated workforce	2017

**Highlighted objectives closely align with the focus of this thesis*

2.4. CO_2 emissions from the energy sector in Nigeria

According to Climatelinks [132]: “*Nigeria’s total GHG emissions in 2014 were 492.44 million metric tons of carbon dioxide equivalent ($MtCO_2e$), totalling 1.01 percent of global GHG emissions*”. With land-use change and the forestry sector accounting for the highest percentage share (38.2%) of the sectoral distribution of GHG emissions [132]. The energy, waste, agriculture and industrial sectors accounted for the remaining share of the distribution at 32.6%, 14%, 13% and 2.1% respectively [132].

Nigeria’s energy sector contributes to countrywide GHG emissions through its oil and gas, power and transportation sectors. The oil and gas sector’s contribution can be attributed to gas flaring in its upstream subsector due to technology inadequacies amongst others [131]. The power sector’s contribution can be attributed to base load power plants (gas-fired) and power supply unreliability leading to the proliferation of diesel and petrol generators in the multi-sectors [1, 100]. The transportation sector’s contribution stems from diesel and petrol fuelled vehicles. The road transportation subsector in Lagos state exemplifies aggregated emissions, as vehicles are caught up in traffic congestions for extended hours on a day-to-day basis [131].

2.5. Issues arising

Gaining insight into Nigeria’s energy sector, the following issues still need to be addressed:

- Although Nigeria is a signatory to the Paris climate accord [49] and measures in mitigating climate change have been covered in some of the policy documents, climate policies need to be further defined and streamlined to better guide national efforts;
- It is important electrification goes beyond lighting and provides the quality of power required in sustaining a rise in economic activities. A problem could arise when the level of economic activities in newly electrified communities (especially rural communities) dwarfs the extent to which they can productively utilise their power supply;
- As off-grid sustainable solutions continue to be deployed across the country, a rise in non-harmonised technologies across power systems could present a problem. The implementation of disparate RETs and supporting technologies

per project executed could present a problem in extending electrification. These could cause an impediment to the interconnection of mini-grids serving multiple communities, to the interconnection of mini-grids with the main grid and in emergency situations where a protective scheme deployed in another system has to be replaced in order to maintain uninterrupted power supply to a particular centre, community or institution;

- The non-development of a transactive electricity market (TEM) through mechanisms (e.g. Feed-in-Tariffs (FIT), Time-of-use (ToU) tariffs, net energy metering (NEM), demand-side management (DSM) etc.) that enhance the implementation of policy objectives, still limits the number of pathways that can be fully explored in realising the country's electrification agenda;
- The lack of a defined, structured and continuous approach to energy auditing of the multi-sectors at the government level, creates a paucity (not available, not accessible and not reliable) of granular country-specific energy data. These data could inform policy action and direction, regulations, means of enforcement, advance research on energy requirements that are unique and specific to a community, an industry, a sector, a state, the country and the broader region.

2.6. Research questions

Based on earlier discussions and the issues arising from an overview of Nigeria's energy sector, this thesis intends to answer the following questions:

i. What is the economic, environmental and social cost of unreliable power supply to Nigeria?

ii. How can the gaps identified in the country's electrification agenda be addressed towards driving economic, environmental and social sustainable development?

2.7. Summary

This chapter has been able to outline developments recorded in Nigeria's energy sector along with the anomalies in its power sector based on a timeline of documented events. These anomalies as well as the gaps identified in the federal government's renewed electrification efforts present an opportunity for this thesis to propose theoretical and practical contributions to Nigeria's electrification plan and, by extension, its socioeconomic and environmental development.

CHAPTER THREE

Methods

This research employed mixed methods (qualitative analysis, quantitative analysis, and numerical simulation) in presenting a body of work, holistic in approach with original content and analytical base.

3.1. Case study presentations

The case studies presented in chapters Four and Six were explanatory/interpretive. They formed the building blocks for this body of research. They aided the research by giving it focus and direction i.e. finding sustainable means of electrifying the C&I sector that could be extended/replicated in the multi-sectors of the economy. Chapter Four introduced a case study on Nigeria’s industrial sector that highlighted the economic cost of unreliable power grid supply and independent fossil fuel power solutions (petrol and diesel generators). Chapter Six introduced a case study on Nigeria’s commercial sectors’ power system solutions to further highlight their unreliability as well as elicit their inefficiency, high cost of operation and unsustainability.

Reason for selection: The case studies presented an opportunity to introduce originality into the research, by sourcing content directly from the sectors of interest in the country of study, through carefully designed questionnaires and surveys. The focus on the C&I sector is in light of Nigeria’s aim to diversify its economy away from crude oil dependence and transition to a more industrialised; self-reliant economy. The C&I sector through the design and implementation of sustainable power solutions is seen as a viable option in extending electrification to the multi-sectors.

Application for this study: The case study introduced in chapter Four was sector-specific (manufacturing/industry). It was based on electricity costs data sourced by the collaborative efforts of stakeholders (GIZ – The Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH., and NEMSA) in Nigeria’s electricity sector. The dataset covered the electricity costs incurred by 14 businesses (from food and beverage production to motor vehicle assembly) in five of the six geo-political zones in the country for 2014 and 2015. The study created room for a problem-centric (identifying the economic cost of unreliable power supply in sustaining business operations) and solution-centric (how can these problems be addressed) approach. The case study was also a vehicle towards analysing real life problems and proffering solutions with real life applicability. For the study in chapter Four, three scenarios were presented to better define/quantify the problem and assess the impact of the solutions. The approach of this chapter and the results realised from its case study were focal in defining the content of chapters Five, Six and Seven.

The case study in chapter Six was also sector-specific (commercial). It was introduced to elicit the impact of power systems solutions on the problems created by unreliable power supply in Nigeria. This was assessed considering economic and environmental factors. The study also helped in exploring disparate solutions that could address Nigeria's electric power supply unreliability i.e. scalable solutions for application in the multi-sectors (residential and C&I). Focus on the multi-sectors, encapsulated demographic (underserved and unserved communities) characteristics. The case study focussed on commercial centres (plazas) in Nigeria's capital – Abuja. Identifying the problem and defining the study was informed by personal experience volunteering in a commercial business. The definition of the case study outlined its requirements (data and solution wise). A solution-centric approach was also followed. Solutions realised have real life applicability, scalable for a myriad of applications.

Review of the literature underpinning the method: Zainal's [155] research, covered the design, categorisation, advantages and disadvantages of case studies as a research method. The research elicited case study as a method applied in various learning fields i.e. Sociology, Law and Medicine. Her review of the literature, presented two case study design structures i.e. single case and multi-case. The former was widely criticised for its lack of robustness and a lack of confidence in the general applicability of results. On the other hand, multi-case was considered robust with results adoptable/reflective of real life events/outcomes. Pattern-matching (linking several pieces of information from a case to other theoretical propositions) was integral to the multi-case design structure. The research further elicited the benefit of pattern-matching in making the design structures robust, with better confidence in the findings of such studies. With regards to categorisation, the research initially highlighted three types – exploratory, descriptive and explanatory. The first, exploring the phenomena found in the data. The second, describing the phenomena found in the data with the final type examining and explaining same. The research further highlighted two other study categories i.e. interpretive and evaluative. In interpretive case studies, the researcher examines the data, conceptualises it and draws assumptions that challenge or support them. Evaluative studies extend from interpretive and introduce judgement to the phenomena found in the data. In tailing off discussions, the author presented some advantages and disadvantages of case studies as a research method. With advantages such as; it allows for examining the data within the context of its use, applicability of qualitative and quantitative analysis and the ability to explore the complexities of real-life scenarios that otherwise may be difficult to capture when applying other research methods (experiments and surveys). Nonetheless, disadvantages like its lack of rigour, its extensive process with excessive documentation, limitations to generalising findings i.e. as a result of the small number of subjects explored, as well as its dependency on single case exploration were highlighted.

Ramdas *et al.* [156] presented the case of the square kilometre array (SKA) project in discussing the application of the case study method. The South Africa based project was considered unprecedented and an ideal critical case for applying the method. The main purpose of their study was to investigate how systems engineering is applied to a project in the research and development environment. Their research design followed five key steps i.e. formulating the research questions, identifying the theoretical propositions, defining the unit(s) of analysis, the logic linking the data to the propositions and outlining the criteria for interpreting the findings. The merits of the method applied, was the subjective aspect it captured. With systems engineering focussing on objective views (measurable, quantifiable and verifiable), subjective elements are usually ignored. In highlighting the benefits of the method adopted for their study, the author’s raised a point on the complexities of systems and the growing interactions between both. They also highlighted the fact that in a multidisciplinary engineering team, social influences affect the development and operation of systems and it was down to the systems engineer to understand/navigate the interplay. This is why it is important for qualitative methods (case studies) to capture social elements at the research phase i.e. within the simulation environment. Some of the limitations they presented were the non-inclusion of quantitative data that would have evaluated the project’s performance metrics and forgoing qualitative data (addressing critical and sub-research questions) considered too sprawling to be documented in their report.

3.2. Interviews, Questionnaires and Surveys

Chapter Four employed the use of questionnaires in generating numerical data from industries in five of the six geo-political zones in Nigeria for quantitative analytical study. Chapter Five interviewed the commercial sector and surveyed the commercial and residential sector to better understand the countrywide electricity supply unreliability and perception of sustainable power system solutions towards informing decisions on power system solutions' design and implementation. Chapter Six surveyed the commercial sector to elicit workable data on their commonly-occurring activities, load demand, power system operations and requirement for further quantitative analysis.

Reason for selection: Interviews (semi-structured) and questionnaires/surveys (qualitative analysis) acted as vehicles in extracting original data from the cases studied for quantitative analysis.

Application for this study: Interviewing was fundamental to the first social study in chapter Five. It enabled the thesis further scale the impact of unreliable power supply i.e. at a personal experience level. Representatives (three in all) of the commercial, education and entertainment sector were interviewed. The thesis to an extent, was able to deduce the impact of unreliable power supply on business performance, an individual's quality of life as well as establish a relationship between both. This was possible based on the structure of the questions and setting no restrictions on grammatical correctness of interviewees' responses. It allowed for emotive expressions to be captured in text. For example, to the question: *"Does unreliable electricity supply impact your quality of life away from work? If so, how?",* the commercial sector interviewee responded as*: "Yes it does. You won't be able to eat much when you have an uncovered responsibility to take care of. Your income determines your outcome. If you don't have much income, you can't spend much or else you'll crumble in your business"*. Interviews were conducted using a social media (SM) platform i.e. WhatsApp.

Questionnaires were introduced for the second part of the social study in chapter Five. It enabled the thesis better understand the impact of unreliable power supply on the residential sector as well as gauge their awareness of renewable energy system solutions. Questionnaires in comparison to interviews followed a more defined structure i.e. restricting responses to an options scale. Although options were predefined, the questionnaire avoided leading questions to ensure the collection and collation of usable data. With the rationale that the residential sector housed the workforce of all other sectors, focus was on this sector. Going by the mandatory questions, 233 respondents returned quantifiable responses. For the optional questions, responses were in the range of 233 – 236. Questionnaires enabled a wider reach that would have been arduous with interviews. They also served a different purpose to interviews i.e. intended for extracting quantitative data. The questionnaires were digitally created and distributed. The former via Survey Monkey, with the latter through e-mails and SM platforms i.e. Instagram and WhatsApp.

The survey in chapters Four, Five and Six enabled data collection for qualification and quantification. It was a gateway for collecting electricity costs data in chapter Four and quantifying opinions on the sectoral impact of countrywide electricity paucity in chapter Five. It also helped in better understanding public/societal awareness of renewable energy solutions in chapter Five. It consolidated the presumptive knowledge of commonly-occurring commercial activities in commercial centres and the characteristics of their energy usage/requirements in chapter Six. The survey for chapter Four was digitally created (Microsoft word), digitally (e-mails) and physically (in-person) distributed. As discussed earlier, that of chapter Five was digitally created and distributed. Determining the commonly-occurring commercial activities in chapter Six, was based on visits to the commercial centres considered (40) over a three year period.

Review of the literature underpinning the method: Adhabi and Anozie [157] presented interview as a data collection method for qualitative researchers. They discussed the different structures (structured, semi-structured and unstructured) and the techniques (face-to-face, telephones, e-mails and SM) that facilitate them. They also highlighted the advantages and disadvantages of their application. In qualifying the interview types, structured interviews were defined as rigid and having no room for improvisation i.e. in the interviewer – interviewee interaction. Structured interviews were described as better placed in generating quantitative data. Semi-structured interviews were considered the most used type of the three. Not rigid in structure, they accommodate improvisation/enhanced (with follow-up) questioning of the interviewee. Their flexible nature caters to both individual-specific (in-depth, exploring personal issues) and group interviews. A notable example of semi-structured interviewing are “Focus groups”. Semi-structured interviewing was acknowledged as “ideal” in collecting data for qualitative studies. Unstructured interviews are controlled conversations influenced by the researcher’s interests. They could be non-directive (the researcher has no pre-planned questions) or focused (the researcher eases the subject towards a topic of interest). Despite their non-defined structure, they are still considered a significant means of data collection in qualitative studies. With regards to the research techniques, face-to-face and telephone interviewing were considered the most utilised. Although the advent of technology (SM) has allowed traditional means of interviewing to be accomplished in different ways. An advantage of interview as a method, is that interviewees are allowed room to explain a subject as well as they understand it. This aids the researcher in easily identifying the occurrence of a phenomenon. Other advantages are it allows for extensive data collection, wide data coverage (through telephone and SM facilitated interviews) especially for inaccessible regions, captures visual expressions, saves time and costs. The disadvantages are mostly based on the technique adopted. Face-to-face interviews are time consuming and could be costly, telephone interviews are time constrained, e-mails and SM eliminate the use of physical aids for further justification, they are also easier to introduce bias to the process and non-physical interview techniques cannot adequately capture human expressions. Regardless of the demerits of the interview method, they are still widely used and are considered important in the authenticity of qualitative studies.

Surveys are used in every field of learning/research to gather a range of information (data) on people or processes in a large cohort. They employ methods such as; questionnaires, interviews and documentation review for their data collection [159]. Jones *et al.’s* [158] study discussed the main aspects of designing, implementing and analysing a survey. They also covered survey techniques (personal, telephone, postal and electronic) and how response rates could be improved. In designing surveys, they highlighted the importance of clearly defining the goal, the objectives of the survey, deciding the demographic to be surveyed and properly structuring the questions. In structuring the questions, normalising statements are to be included, maintaining basic language level, avoiding leading questions as well as questions that include negative items and assign causality. Employing the services of a statistician in making the most of the data collected (determining sample size that ensures data validity), was another factor they highlighted. Survey instruments such as; *“Beck Hopelessness scale”* or *“Addenbrooke’s Cognitive Examination”*, were also elicited as models that could improve data validity. For improving response rates, some recommendations were: including non-monetary incentives, employing short questionnaires, using white backgrounds, including pictures and stating the recorded number of responses till date. As a method, the advantages of surveys are they are easy to analyse and they are conducted faster (as well as cheaper) than other methods i.e. observations and experiments [159]. De-merits of surveying are the limitations of questionnaires and unwillingness of respondents to provide information. Some other de-merits are: bias could be introduced to the process, response rates impact result validity and difficulty in formulating the right questions i.e. ease of general (widespread) understanding.

3.3. Qualitative and Quantitative analysis

A cost-benefit analysis (CBA) comparing the current power system to a modified fossil fuelled system and a sustainable power system solution was carried out on data realised through the qualitative analysis of the industrial sector in chapter Four. Qualitative analysis was also employed in chapter Five for obtaining data that informed power system solutions design and implementation in the subsequent chapter. In chapter Six, a systematic quantitative analysis founded on the fundamental pillars of affordability, reliability and sustainability was applied to analyse a range of power system solutions towards realising the most viable for commercial operations. An extensive review of the literature on power system solutions deployed for sub-Saharan (SSA) also informed power systems analysis.

Reason for selection: Qualitative analysis extracted the raw data with quantitative analysis exploring its application in real life scenarios.

Application for this study: Qualitative analysis was employed in chapters Four, Five and Six. The survey of industries in chapter Four created room for electricity costs data to be collected. This was facilitated through carefully structured questionnaires distributed by GIZ. The interviews and survey conducted in chapter Five were important in introducing a social element to the thesis. Digital/SM technology enabled these processes to be carried out remotely. The survey tool also enabled data to be visually represented for perspective. The tool also eased the process of data quantification i.e. the transition from qualitative to quantitative data. The in-person survey adopted in chapter Six unlike the interviews and survey in chapter Five, were non-contingent on opinions and experience. Although social (human) interactions helped in verifying certain assumptions i.e. if a grocery stored existed, when it was not immediately spotted in a commercial centre.

Quantitative analysis was the core of the analytical method for this thesis. A CBA was applied on electricity costs data realised from a survey of industries in chapter Four. The analysis considered present (spot) value of industries electricity costs data in 2014 and 2015. The future value of electricity costs were considered for an eight year period onwards from the base years. Two electrification scenarios were presented alongside the business-as-usual scenario for context and comparative view. The future costs took into account Nigeria’s inflation and discount rates for the period considered. Assumptions guided the scenarios presented. A cost-effective solution with environmental benefits was presented as the best power system solution for industries based on the scenarios considered. A systematic quantitative analysis was applied in chapter Six. A model commercial centre (Olowos plaza) that housed the commonly-occurring commercial activities realised from a survey of commercial centres was created. The composition of the electronic devices/equipment that facilitate the operations/activities of businesses in semi-structured commercial centres were estimated based on past experience volunteering in a commercial centre. Assumptions (business operations, power systems operations and costs consideration) guided the analysis in this chapter. Fourteen power system solutions were analysed against performance metrics of affordability (economic costs – life cycle cost analysis i.e. 20 years), reliability (unmet load – System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI)) and sustainability (environmental costs – emissions reduction i.e. CO_2 tonnes/year). The analysis was considered systematic and non-parochial as it was detailed in its approach. From understanding the dynamics of the commercial centre’s energy demand (sizing of electronic device/equipment, estimating their performance in use, deducing the centre's load profile, energy usage characteristics and user requirements), to meeting it with uninterrupted power supply (power system component parts performance in service, characteristics and requirements for their optimum performance, their economic and environmental implications). Apart from the best performing power system solution, some other solutions were considered practicable.

Review of the literature underpinning the method: Boamah and Rothfub [57] carried out a study in Accra, Ghana, to understand the implication of the energy transition (deployment/adaptation of non-conventional power system solutions/technologies) on society. In gathering data for their study, they conducted face-to-face interviews and observations through home visits. Selecting the interview demographic was based on contact with Ghana's Energy Commission (GEC) and the provision of information on a government-sponsored rooftop solar programme distributing free "500-W solar-PVs" to 200,000 residences. They interviewed 22 households with solar home systems (SHS) – 13 beneficiaries of the rooftop programme, with the others self-financed. The latter group were identified through the snowball sampling method. Due to the nature/structure (not gathering sensitive information) of the interview questions, participants were welcoming and freely participated in the study. General conversations on the state of the nation, frailties of the electricity sector, reasons for the study, certain energy consumption phenomena preceded interviewing. The interview questions were structured but allowed flexibility in the interviewer-interviewee interaction. The principal interviewee was the most conversant with the SHS installation (usually the installer) but was joined by members of the household on occasion. Interview questions covered feelings on the power situation, views on the performance of their energy service company (ESCO), preference or not for energy autonomy, the electric components/devices powered by the SHS amongst others. Interviews were augmented by observations especially with regards to the SHS installation. Observations were recorded in the field research booklet. Outstanding issues not immediately clarified were elucidated via SM (WhatsApp) and telephone calls. MaxQDA, a computer programme for analysing qualitative data aided in the analysis of the data realised i.e. expressions, comments and quotations. They stressed that the method (interview together with the sampling strategy) adopted for their study elicited patterns that explained the drive in the adaptation of SHS as well as its implication for societal change.

Wojuola and Alant [64] conducted a study to evaluate the public's understanding of RETs with regards to sustainable living. They adopted a sequential mixed-method for their research. This embodied the form of a survey distributed to a sample size of 600 people from Ibadan, Akobo and Asi (South-West, Nigeria). Interviews with four focus groups, comprising 23 participants from the survey, complemented the research. The qualitative element of their survey focussed on the analysis of the participants' experiences, with the quantitative part evaluating variables to establish a pattern. They employed a stratified quota sampling technique with 14 close-ended questions as the survey instrument. Five questions, focussed on knowledge and beliefs with the remainder on perception and attitude (with regards to RE and sustainable living). The research instrument was tested through a pilot study that involved 30 participants, and was conducted alongside the main study. Responses from respondents (pilot study), returned no anomalies. The research instrument also passed the internal consistency test based on "Cronbach's alpha reliability test". Quantitative data was analysed using SPSS statistic software, with qualitative data analysed by a thematic method.

Batchelor *et al.'s* [160] study adopted a multi-criteria decision analysis (MCDA) method i.e. taking into consideration socio-cultural, political, technical and economic factors expected to affect the uptake and potential impact of electric cooking (eCook) in African countries. A global market assessment (GMA) database constructed in Microsoft Excel (also available in the public domain), by one of the researchers was the source of quantitative data used in the study. Weightings were assigned to indicators (infrastructure, culture, human, physical and economics) that could influence the local market (per country) uptake of PV-eCook. Simple Multi-Attribute Rating Technique (SMART) was the MCDA technique applied in the study. They presented the limitations to their approach as; possible introduction of bias through weightings, per country datasets were not exhaustive, the technique applied was limited by its quantitative and hard to contextualise nature as well as the pace of change within specific countries might not be adequately captured by the static indicators used as performance metrics.

3.4. Numerical simulation

Chapter Seven applies numerical simulation in exploring a more expansive range of power system solutions when compared to the analysis in chapter Six. Also, the application of numerical simulation, focusses on mining country-specific typical meteorological year (TMY) data. These data is used in the studies presented in chapter Six and chapter Seven.

Reason for selection: To validate earlier obtained results and expand the analytical approach.

Application for this study: The solar irradiation data for Abuja, Nigeria used in chapters Six and Seven of the thesis was downloaded from Copernicus Atmospheric Monitoring Service (CAMS) – the solar resource simulation software. To validate the results obtained in chapter Six, 20,200 candidate power system solutions were considered. An expansion from the 14 candidate solutions considered in chapter Six. The standalone and hybrid power system configurations were the same as the ones considered in chapter Six. Except for the omission of the “Integrated Hybrid Generator-based System (IHGS)”, all other assumptions and considerations subsisted. Solutions were analysed against the performance metrics of affordability (economic costs – life cycle cost analysis i.e. 20 years), reliability (unmet load – SAIDI & SAIFI) and sustainability (environmental costs – emissions reduction i.e. CO_2 tonnes/year). The cost function equations were deduced from the equations of the straight line graph of solar-PV and energy storage system capacities quantitatively determined in chapter Six. The generator system cost and emissions reduction function were based on iterative computations of the systems’ capacities and frequency of usage, assuming a fixed reduction in costs per decrease in capacity size. Using these equations, a matrix of solutions (20,200) created in spreadsheet were then exported to Matlab to determine the optimum solution. The simulation followed three orders of elimination in realising a viable solution. The first order eliminated solutions for not meeting the commercial centre’s average and peak load demand. The second order, eliminated solutions based on pre-defined technical operating parameters (TOPs) and the final order eliminated solutions in order of priority level i.e. environmental metrics were prioritised over economic metrics in realising the single most-viable solution.

Review of the literature underpinning the method: Foles *et al.* [101] employed Matlab in evaluating the techno-economic viability of solar-PV and solar-PV plus energy storage systems for the residential sector in three representative Portuguese locations. The net present value (NPV), the total life cycle cost (TLCC), the levelized cost of energy (LCOE), the simple payback period (SPB), the internal rate of return (IRR) and the benefit-to-cost ratio (B/C ratio) were the indicators that guided their analysis.

Hittinger and Siddiqui [150] considered 1020 locations in the USA when analysing the economic viability of grid defected power systems (solar-PV and battery storage) using their energy system model (ESM) developed in Matlab. The model defined certain techno-economic/operational parameters i.e. unmet/residual load, PV/battery operating conditions, the hybrid system's operation constraints, LCOE, that applied in their study.

Some limitations of numerical simulation methods, lie in the parameters and data that define the model [161]. Also, the precision (and evaluation) of results might present a problem if the technical parameters and operating conditions are not accurately computed (do not significantly incorporate/represent the real life conditions of the subject studied) [161]. Furthermore, the number of parameters defined increases the difficulty in finding an optimal/best-fit solution [161].

The different methods implemented within this body of research were selected for research robustness i.e. providing analytical depth and academic rigour.

CHAPTER FOUR

The economic impact of unreliable power supply in Nigeria

Preamble

The current situation of epileptic power supply and incessant power outages nationwide, has left industries, corporations, households and businesses with no other option than to find alternative means of generating their own electricity [19, 20]. This is mainly to ensure security of supply and more so cushion the unfavourable effect of power outage on operations (which usually translates as monetary losses for the industrial sector).

The industrial sector in Nigeria is made up of factories producing a range of products varying from food, beverages, tobacco, textiles, footwear, wood, plastic, rubber and paper; to paint, cement, electrical materials and iron/steel [1]. Pharmaceuticals and motor vehicle assembling are also industrial activities in Nigeria. Being an energy intensive sector, the adverse effect of power supply unreliability on multi-sectoral growth and development comes to the forefront. Countrywide brownouts and blackouts have impacted industrial productivity, limiting their economic contribution [12] as industries continue to incur significant costs in ensuring uninterrupted power supply [1].

The industrial sector, for example, relies heavily on the use of heavy duty diesel electric power generators in ensuring continued work operations. The use of these generators has resulted in the high cost of energy as it constitutes 40% of the country's production cost [21]. According to the Manufacturers Association of Nigeria (MAN), more than ₦1.8 billion (US$11.340 million) is spent weekly on the operation and maintenance of these generators industry-wide [21]. Furthermore, with the removal of subsidy on diesel, pump diesel fuel retails at ₦158 (US$0.80) per litre, a similar price to that of China [22], although the cost of production is nine times higher than in China. In a survey reported by [20], improvements in grid reliability were found to increase respondents' willingness to dispose of their power generators, particularly in the case of small business owners.

The electricity paucity has led to some transnational corporations relocating their regional production facility to other West African states [13], with major corporations such as; GlaxoSmithKline and Coca-Cola circumventing grid power supply unreliability by taking advantage of Nigeria’s natural resource (crude oil) in becoming captive power generators [14, 15]. This power supply solution can be impractical for most small – medium scale industries due to high capital and operational expenditure. Another power solution involves industries collaborating with DisCos (In-DisCos) by making substantial investments in their power supply infrastructure [1]. Injection substations are installed with dedicated sub-transmission (33 kV) lines erected in wheeling power to industrial facilities [1].

The viability of the “In-DisCos” power supply solution becomes questionable as industries experience significant reductions in their daily power supply access. Furthermore, heavy duty diesel generators (irrespective of initial investments in power infrastructure) are being deployed to address the “new” power supply shortfall (that the collaboration sought to address) created by connecting a growing number of residential customers to sub-transmission lines.

A significant portion of this chapter is from the paper – The economic cost of unreliable grid power in Nigeria. African Journal of Science, Technology, Innovation and Development. 11 (2), pp. 1 – 11. https://doi.org/10.1080/20421338.2018.1550931

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Abstract

The ever increasing demand for electrical power in Nigeria, coupled with a limited supply, have restricted the nation's socioeconomic development. The country's policy makers, aware of this, have formulated and enacted energy development policies in recent years targeted at diversifying the current electricity mix and increasing electrification to rural settlements. Despite these efforts, electricity infrastructure projects have been side-lined, power outages are common and grid unreliability is costing industry significant amounts to secure the electricity supply necessary for business sustainability and profitability.

This paper presents the current state of the electricity industry in Nigeria and argues the case for integration of renewable energy technologies. A case study is presented based on electricity cost information collected from a survey of Nigerian industry. Three future electricity supply scenarios are presented: a do-nothing or business-as-usual scenario; a scenario of increased reliance on grid power due to improvements in reliability; and a scenario involving shifting some of the current diesel on-site generation to solar photovoltaics. It is shown that increasing the utilization of renewable sources could significantly reduce the costs and CO_2 emissions incurred due to the current reliance on self-generation, primarily using diesel generators, amidst grid unreliability.

Keywords: diesel generators; electricity sector; Nigeria; power generation; power supply; renewable energy

4.1. Introduction

It is essential that Nigeria's electricity mix of natural gas and hydropower be expanded for power generation sustainability. With a growing population and forecast of just over 262 million people by the year 2030 [7] connection of the entire country to the national grid is fading especially considering the practical difficulties and expense of constructing new transmission lines. The federal government aware of this have started evaluating more sources for diversified electricity production and in April 2015 supporting this cause, the Federal Executive Council (FEC) approved the National Renewable Energy and Energy Efficiency Policy (NREEEP) [34].

The NREEEP document addresses key areas such as; renewable energy supply & utilisation, renewable energy pricing and financing; legislation; regulation and standards; energy efficiency and conservation; renewable energy project implementation issues; research and development; capacity building and training; gender and environmental issues and planning and policy implementation [34]. In summary, the policy's thrust is the optimal utilisation of Nigeria's energy resources for sustainable development.

The current situation of epileptic power supply and incessant power outages nationwide, has left industries, corporations, households and businesses with no other option than to find alternative means of generating their own electricity [19, 20, 105]. This is mainly to ensure security of supply and more so cushion the unfavourable effect of power outage on operations (which usually translates as monetary losses for the industrial sector).

The industrial sector, for example, relies heavily on the use of diesel electric power generators in ensuring continued work operations. The use of these generators has resulted in the high cost of energy as it constitutes 40% of the country's production cost [21]. According to the Manufacturers Association of Nigeria (MAN), more than ₦1.8 billion (US$11.340 million) is spent weekly on the operation and maintenance of these generators industry-wide [21]. Furthermore, with the removal of subsidy on diesel, pump diesel fuel retails at ₦158 (US$0.80) per litre, a similar price to that of China [22], although the cost of production is nine times higher than in China. In a survey reported by [20], improvements in grid reliability were found to increase respondents' willingness to dispose of their generators, particularly in the case of small business owners.

Practical solutions are required to reduce the dependency on diesel generators while maintaining the connectivity and reliability of supply to the majority of the country not served by a reliable connection. At the forefront should be the implementation of off-grid and mini/micro grid solutions especially for rural communities, settlements and the industrial sector. Previous studies have shown that some regions of the country possess considerable exploitable resources in wind and, in particular, solar energy [35, 36] and have demonstrated the cost competitiveness of electricity from hybrid renewable systems with grid-supplied electricity [37].

Therefore, discussions in this paper are broken down into sections with the objective of eliciting the cost incurred by the industrial sector in sustaining operations as a result of grid unreliability and interrupted power supply. Section 4.2 gives a background on Nigeria's electricity sector, section 4.3 discusses the methods adopted, and section 4.4 analyses the results of the case study carried out on the industrial sector, with section 4.5 covering the discussions and the conclusion in section 4.6.

4.2. Nigeria’s electricity sector

The promulgation of the Electricity Power Sector Reform (EPSR) Act in 2005, led to the unbundling of the wholly government owned National Electric Power Authority (NEPA) into eighteen “successor” companies i.e. six generation companies (GenCos), one transmission company (Transmission Company of Nigeria (TCN)) and eleven distribution companies (DisCos). These companies remained under a holding company – Power Holding Company of Nigeria, (PHCN) until September 2013 when they were conceded and subsequently handed over to investors (November, 2013) in line with the power sector reform objectives [5]. The Nigerian Electricity Supply Industry (NESI), like many other electricity markets, delivers the electricity supply value chain starting from generation, through transmission and ending with the distribution of electricity to consumers.

Generation subsector

Nigeria’s energy mix of natural gas (combined & simple cycle) and hydro-power plants at 84% and 16% respectively, is integrated for central systems operation at the National Control Centre (NCC), Oshogbo in Osun State [5]. For stability and system reliability, regional control centres (RCCs) are also located in three other areas of the country (Shiroro - Niger State, Ikeja West - Lagos State and Benin City - Edo State). With total dependence on two sources of electricity generation and approximately 82% of generating plants in the southern region of the country, the nation’s electricity security, stability and reliability continues to be at risk. Figure 4.1 shows Nigeria’s population and power plant distribution.

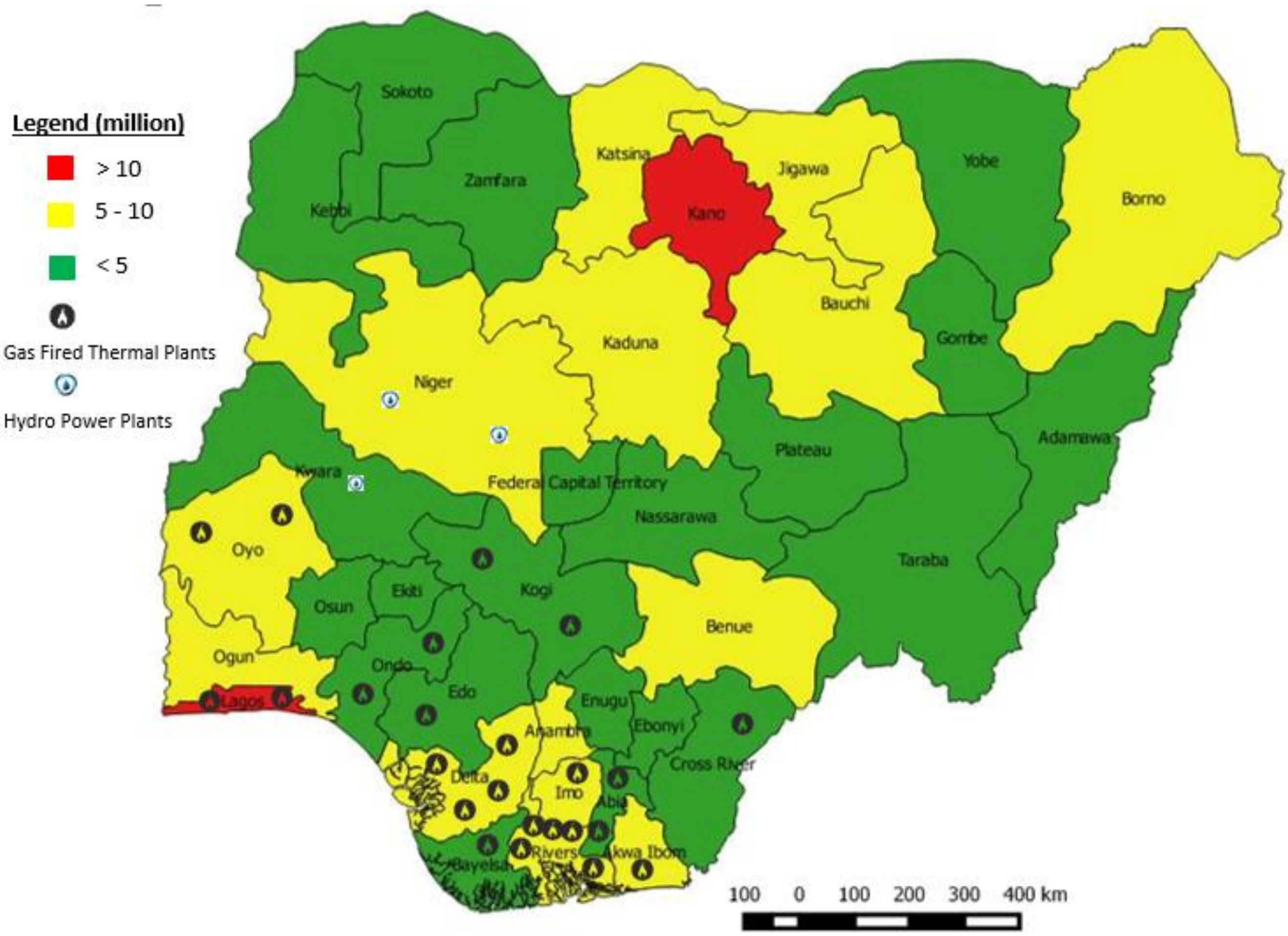


Figure 4.1 – Map of Nigeria showing population and power plant distribution

As of 2015, the nation's generation capacity was approximately 12.5 GW, with average available capacity of 7.14 GW and operational capacity of 3.9 GW [38]. That being said, Nigeria achieved a milestone peak generation of 5.1 GW on 2nd February, 2016 with maximum wheeled energy of 109 GWh recorded on the 26th January, 2016 [6]. Table 4.1 shows Nigeria's electricity generation profile from 2010 to 2015.

Figure 4.1– Nigeria's electricity generation profile – Adapted [8]

Year	Av. Gen Availability (MW)	Max Peak Gen (MW)	Max daily energy Gen (MWh)	Total energy Gen (MWh)	Total energy sent out (MWh)	Per Capita energy supplied (kWh)
2010	4,030.5	4,333.0	85,457.5	24,556,331.5	23,939,898.9	153.5
2011	4,435.8	4,089.3	90,315.3	27,521,772.5	26,766,992.0	165.8
2012	5,251.6	4517.6	97,718.0	29,240,239.2	28,699,300.8	176.4
2013	5,150.6	4458.2	98,619.0	29,537,539.4	28,837,199.8	181.4
2014	6,158.4	4395.2	98,893.8	29,697,360.1	29,013,501.0	167.6
2015	7,141.2	4883.9	106,288.0	33,980,040.8	31,465,920.3	170.1

Maintenance and repair works constrain available generation capacity whilst operational capacity is constrained by [38]:

i. Insufficient gas supply due to low production;
ii. Infrastructure deficit and vandalism;
iii. Poor water management;
iv. High frequency due to demand imbalances;
v. Line constraints also bordering on inadequate grid infrastructure.

Transmission subsector

The transmission subsector is charged with bulk wheeling the generated power through high voltage transmission lines and sub-stations to deliver electricity at lower voltage levels for onward supply to the consumer by the distribution companies [5]. The transmission network consists of 159 sub-stations with a total transformation capacity of 19,000 MW spanning 15,022 km in total length [38]. The national grid has a maximum wheeling capacity of 5,300 MW, which is currently above the operational generation capacity but still substantially below the installed capacity.

The grid is plagued by partial and full system collapses and forced outages owing to a poor voltage profile, limited control infrastructure, ineffective maintenance and poor system management [38]. Figure 4.2 shows a decline in the number of system collapse over the years (2009 – 2015) but this remains slightly above the benchmark range of 2 to 6 per annum for emerging countries [38].

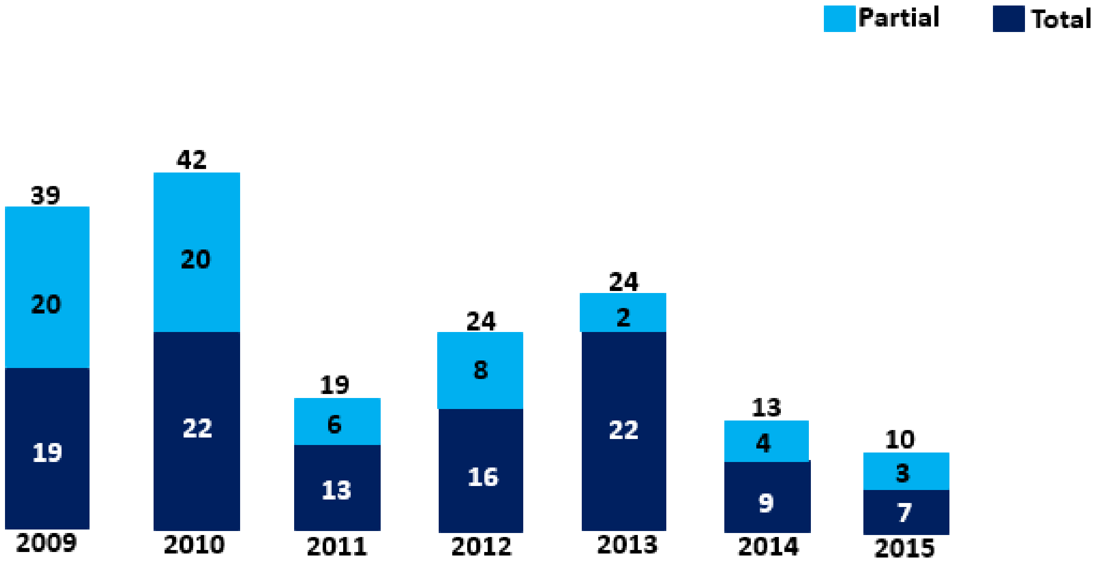


Figure 4.2 – Number of system collapses over the years – Adapted [38]

Distribution subsector

This serves as the customer interface platform of the value chain with the distribution companies responsible for retailing electricity to the end user. Nigeria's peak demand as of 2015 was estimated at 12,800 MW, whilst her electrification rate at 40% with urban and rural electrification rates at 65% and 28% respectively (translating to approximately 95 million people without access to grid power supply) [125]. In 2014, approximately 46% of energy was lost through technical (12%), commercial (6%) and collection (28%) losses [38]. The distribution system constitutes a problem, primarily because of the poor condition of the networks and a large number of unmetered consumers [38]. These issues contribute to electricity distribution losses countrywide. Eleven distribution companies (DisCos) with regional coverage areas, collectively cover the entire country as indicated in Table 4.2.

Table 4.2 – Distribution companies and their coverage areas

S/N	DisCos	Coverage Areas (States)
1	Abuja Electricity Distribution Company	F.C.T, Niger, Kogi and Nasarawa
2	Benin Electricity Distribution Company	Edo, Delta, Ondo and part of Ekiti
3	Eko Electricity Distribution Company	Lagos
4	Enugu Electricity Distribution Company	Enugu, Abia, Anambra, Imo and Ebonyi
5	Ibadan Electricity Distribution Company	Oyo, Ogun, Osun, Kwara and part of Ekiti
6	Ikeja Electricity Distribution Company	Lagos
7	Jos Electricity Distribution Company	Plateau, Bauchi, Benue and Gombe
8	Kaduna Electricity Distribution Company	Kaduna, Sokoto, Kebbi and Zamfara
9	Kano Electricity Distribution Company	Kano, Jigawa and Katsina
10	Port Harcourt Electricity Distribution Company	Rivers, Cross-River, Bayelsa and Akwa-Ibom
11	Yola Electricity Distribution Company	Adamawa, Yobe, Borno and Taraba

4.3. Method

To further elicit the problem of electricity supply country-wide, a case study on the industrial sector was presented with a cost benefit analysis carried out on the data supplied by industries. Three future scenarios were created to guide our analysis and enable us quantify the unreliability of electricity supply as well as determine its economic impact on Nigeria's industrial sector in particular**.**

4.3.1. A case study – The cost of unreliable grid power on manufacturing in Nigeria

This case study consolidates earlier discussions in this paper on the current state of electricity supply in Nigeria. It analyses the manufacturing industry in Nigeria, by examining the added costs to their operations as a result of unreliable grid power. The manufacturing sector is selected for analysis due to its significant contribution to the nation's GDP [8]. Furthermore this sector, in the wake of falling oil prices, could be critical to the government's intensified efforts of diversifying the economy and reducing its overdependence on crude oil export earnings**.**

4.3.1.1. Data presentation

The industrial sector in Nigeria is made up of factories producing everything from food, beverages, tobacco, textiles, footwear, wood, plastic, rubber and paper to paint, cement, electrical materials and iron/steel. Pharmaceuticals and motor vehicle assembling are also industrial activities in Nigeria. Therefore, data presented in this section (particularly the ones included in Tables 4.3-8) have been collated from questionnaires circulated by Nigerian Electricity Management Services Agency (NEMSA) to individual manufacturing industries. Other data presented and assumptions made within this section have been generated directly or indirectly through contact with industries.

Although, the list of manufacturing industries surveyed is not exhaustive, it accounts for industries in all but one geo-political zone of the country and is representative of industry-wide electricity consumption patterns. Tables 4.3-8 show the industry types by region and their electricity consumption patterns in monetary terms (electricity and generator fuel costs) for the years 2014 and 2015. A total of 20 respondents' data were released by NEMSA of which only 14 could be used for this analysis (due to incompleteness and illegibility). All costs are represented in million Naira (₦ - million) with the formula - ($\overline{X}=\frac{(\sum X)}{N}$) used in deriving the average electricity cost.

Table 4.3 – Cost of electricity to factories in the North-West region

Region 1 – North West					
Year		**2014**		**2015**	
Name	**Type**	**Grid Supply Costs (₦ - million)**	**Self-Generation (Fuel) Costs (₦ - million)**	**Grid Supply Costs (₦ - million)**	**Self-Generation (Fuel) Costs (₦ - million)**
Factory A	Beverages	51.2	15.8	53.6	15.8
Factory B	Beverages	923.7	557.6	752.3	422.8
Factory C	Textile	70	40	90	36
Factory D	Electrical (Cables)	34	23.9	47.7	22.4
Total		**1,078.9**	**637.3**	**943.6**	**497**

Table 4.4 – Cost of electricity to factories in the North-Central region

Region 2 – North Central					
Year		**2014**		**2015**	
Name	**Type**	**Grid Supply Costs (₦ - million)**	**Self-Generation (Fuel) Costs (₦ - million)**	**Grid Supply Costs (₦ - million)**	**Self-Generation (Fuel) Costs (₦ - million)**
Factory E	Food (Flour)	12	71.3	14.4	82.4
Factory F	Food (Cereal)	170	177	128	260
Factory G	Food (Cereal)	19.5	21	20.1	26
Total		**201.5**	**269.3**	**162.5**	**368.4**

Table 4.5 – Cost of electricity to factories in the North-East region

Region 3 – North East					
Year		**2014**		**2015**	
Name	**Type**	**Grid Supply Costs (₦ - million)**	**Self-Generation (Fuel) Costs (₦ - million)**	**Grid Supply Costs (₦ - million)**	**Self-Generation (Fuel) Costs (₦ - million)**
Factory H	Electrical (Cables)	2.8	5.2	3.3	4.7
Factory I	Beverages	38.4	274.2	45.6	274.8
Total		**41.2**	**279.4**	**48.9**	**279.5**

Table 4.6 – Cost of electricity to factories in the South-West region

Region 4 – South West					
Year		**2014**		**2015**	
Name	**Type**	**Grid Supply Costs (₦ - million)**	**Self-Generation (Fuel) Costs (₦ - million)**	**Grid Supply Costs (₦ - million)**	**Self-Generation (Fuel) Costs (₦ - million)**
Factory J	Food(Processed Meat)	235.7	53	285.2	61.7
Factory K	Iron/Steel	42.9	49.3	44.7	22.9
Factory L	Iron/Steel	364.9	2.2	350	0.7
Factory M	Iron/Steel	0.9	17.3	0.6	14.4
Total		**644.4**	**121.8**	**680.5**	**99.7**

Table 4.7 – Cost of electricity to factories in the South-East region

Region 5 – South East					
Year		**2014**		**2015**	
Name	**Type**	**Grid Supply Costs (₦ - million)**	**Self-Generation (Fuel) Costs (₦ - million)**	**Grid Supply Costs (₦ - million)**	**Self-Generation (Fuel) Costs (₦ - million)**
Factory N	Beverages	7.1	8.6	7.7	9.1
Total		**7.1**	**8.6**	**7.7**	**9.1**

Table 4.8 – Total and average costs of electricity to the factories in 2014 and 2015

Year	**2014**		**2015**	
Source of Supply	**Grid Supply Costs (₦ - million)**	**Self-Generation (Fuel) Costs (₦ - million)**	**Grid Supply Costs (₦ - million)**	**Self-Generation (Fuel) Costs (₦ - million)**
Grand Total (₦)	**1,973.1**	**1,316.3**	**1,843.1**	**1,253.7**
Average (₦)	**140.9**	**94**	**131.7**	**89.6**
Average cost implication of electricity supply in percentage (%)	**60**	**40**	**59.5**	**40.5**

4.4. Analysis

In this section, a cost benefit analysis of the data presented is carried out to determine the enormity of the costs incurred by factories in order to sustain their operations. For broader understanding use US$1 = ₦180 (Central Bank of Nigeria (CBN) exchange rate in 2014/2015) [16].This exchange rate holds for the period of data collected (2014 and 2015).

Tables 4.9, 4.10 and 4.11 show Cost Benefit Analysis calculations for “Company X” over a 10 year period.

Table 4.9 – Scenario 1 of company X’s cost-benefit analysis of operating a manufacturing plant in Nigeria

Data Required	**Costs (₦ - million)**
Generator costs (immediate payment)	50 x 2 = 100
Year 1 Electricity costs	140.9
Year 1 Fuel costs	94
Year 2 Electricity costs	131.7
Year 2 Fuel costs	89.6
Years 1 – 10 O&M costs	0.2/Year

Scenario 1 – Business as Usual (Maintain the current system of operation)

Year	**Costs (₦ - million)**						**Benefits (₦ - million)**
	Immediate Payment	Electricity	Fuel	O&M	Total Costs	PV of Total Costs	PV of Benefits
1	100	140.9	94	0.2	335.2	319.2	0
2	0	131.7	89.6	0.2	221.4	200.8	0
3	0	141	94	0.2	235.2	203.2	0
4	0	141	94	0.2	235.2	193.5	0
5	0	141	94	0.2	235.2	184.3	0
6	0	141	94	0.2	235.2	175.5	0
7	0	141	94	0.2	235.2	167.2	0
8	0	141	94	0.2	235.2	159.2	0
9	0	141	94	0.2	235.2	151.6	0
10	0	141	94	0.2	235.2	144.4	0
Grand -Total of Costs and Benefits (₦ - million)					**2,438.2**	**1,898.9**	**0**

As no benefits are recorded for the 10 year period, the present value (PV) of benefits would be zero for the duration considered. Therefore, the net PV (NPV) in Naira (₦ - million) = - 1,898.9

Calculating discount rate taking into account inflation:
Where discount rate = 14% and inflation = 8.8%
Therefore; Real discount rate = (1 + discount rate)/(1 + inflation rate) – 1
= (1+14%)/(1+8.8%) – 1
~ 5%

Other considerations for this analysis:

No Benefits

Year(s)	**Costs (₦ - million)**
1	Generators cost (Immediate payment), Electricity costs, Fuel costs and O&M costs
2 - 10	Electricity costs, Fuel costs and O&M costs

Table 4.10 – Scenario 2 of company X's cost-benefit analysis of operating a manufacturing plant in Nigeria

Data Required	**Costs (₦ - million)**
Generator costs (immediate payment)	50 x 2 = 100
Year 1 Electricity costs	140.9
Year 1 Fuel costs	94
Year 2 Electricity costs	131.7
Year 2 Fuel costs	89.6
Years 1 & 2 O&M costs	0.2/Year
Years 3 – 10 O&M costs	0.1/Year

Scenario 2 – Improvement in Grid Power

Year	**Costs (₦ - million)**					
	Immediate Payment	Electricity	Fuel	O&M	Total Costs	PV of Total Costs
1	100	140.9	94	0.2	335.2	319.2
2	0	131.7	89.6	0.2	221.4	200.8
3	0	141	18	0.1	159.1	137.4
4	0	141	18	0.1	159.1	130.9
5	0	141	18	0.1	159.1	124.7
6	0	141	18	0.1	159.1	118.7
7	0	141	18	0.1	159.1	113.1
8	0	141	18	0.1	159.1	107.7
9	0	141	18	0.1	159.1	102.6
10	0	141	18	0.1	159.1	97.7
Grand -Total of Costs (₦ - million)					**1,829.4**	**1,452.7**

Year	**Benefits (₦ - million)**				
	Sale of Generator	Fuel Savings	O&M Savings	Total Benefits	PV of Total Benefits
1	0	0	0	0	0
2	0	0	0	0	0
3	41.6	72	0.1	113.8	98.3
4	0	72	0.1	72.1	59.3
5	0	72	0.1	72.1	56.5
6	0	72	0.1	72.1	53.8
7	0	72	0.1	72.1	51.2
8	0	72	0.1	72.1	48.8
9	0	72	0.1	72.1	46.5
10	0	72	0.1	72.1	44.3
Grand -Total of Benefits (₦ - million)				**618.4**	**458.6**

With the same discount rate i.e. 5% used in scenario 1 still valid, we calculate the NPV in Naira (₦ - million)as:

458.6 – 1,452.7 = - 994.1

Other considerations pertinent to this analysis:

Generator cost depreciation over 2 years in Naira (₦ - million):

Using sum of the year digits method and assuming that the residual/salvage value is 10% of initial purchase price;

Therefore residual salvage value is 10% of 50 million = 5 million

Depreciation in first year of operation = (50 - 5) x 20/210 = 4.3

Depreciation in second year of operation = (50 - 5) x 19/210 = 4.1

Total Depreciation over the two year period = 8.4

Value of Asset – Depreciation (50 – 8.4) = ₦ 41.6 million

Other considerations pertinent to this analysis cont’d		
Year(s)	**Costs (₦ - million)**	**Benefits (₦ - million)**
1	Generators cost (Immediate payment), Electricity costs, Fuel costs and O&M costs	No benefits recorded
2	Electricity costs, Fuel costs and O&M costs	No benefits recorded
3	Electricity costs	Money recouped from selling ½ diesel/petrol generators, savings on O&M and average savings on fuel costs
4 - 10	Electricity costs	Savings on O&M and average savings on fuel costs

Table 4.11 – Scenario 3 of company X's cost-benefit analysis of operating a manufacturing plant in Nigeria

Data Required	**Costs (₦ - million)**
Generator costs (immediate payment)	50 x 2 = 100
Year 1 Electricity costs	140.9
Year 1 Fuel costs	94
Year 2 Electricity costs	131.7
Year 2 Fuel costs	89.6
Year 1 – 2 O&M costs	0.2/Year
Year 3 – 10 O&M costs	0.1/Year
Year 3 Land costs (immediate payment)	25
Year 3 Charge controllers (immediate payment)	0.24 x 5 = 1.2
Year 3 Batteries (immediate payment)	0.044 x 320 = 14.3
Year 3 Inverters (immediate payment)	4.6
Year 3 Installation costs (immediate payment)	14.1
Year 8 Batteries replacement (immediate payment)	0.044 x 320 = 14.3
Year 8 Re-installation costs (immediate payment)	1.4
Years 3 – 10 Annual O&M of RES	0.424/Year

Scenario 3 – Complementing RES with Diesel Generation

Year	**Costs (₦ - million)**					
	Immediate Payment	Electricity	Fuel	O&M	Total Costs	PV of Total Costs
1	100	140.9	94	0.2	335.2	319.2
2	0	131.7	89.6	0.2	221.4	200.8
3	59.2	0	18	0.524	77.8	67.2
4	0	0	18	0.524	18.5	15.2
5	0	0	18	0.524	18.5	14.5
6	0	0	18	0.524	18.5	13.8
7	0	0	18	0.524	18.5	13.2
8	15.7	0	18	0.524	18.5	23.2
9	0	0	18	0.524	18.5	11.9
10	0	0	18	0.524	18.5	11.4
Grand -Total of Costs (₦ - million)					**779.7**	**690.4**

Year	**Benefits (₦ - million)**				
	Sale of Generator	Electricity and Fuel Savings	O&M Savings	Total Benefits	PV of Total Benefits
1	0	0	0	0	0
2	0	0	0	0	0
3	41.6	213	0.1	254.7	220.1
4	0	213	0.1	213.1	175.3
5	0	213	0.1	213.1	167
6	0	213	0.1	213.1	159
7	0	213	0.1	213.1	151.4
8	0	213	0.1	213.1	144.2
9	0	213	0.1	213.1	137.4
10	0	213	0.1	213.1	130.8
Grand -Total of Benefits (₦ - million)				**1,746.4**	**1,285.2**

With the same discount rate still valid, we calculate the NPV in Naira (₦ - million) as:
1,285.2 – 690.4 = 594.8

Other considerations pertinent to this analysis:

<u>Generator cost depreciation over 2 years in Naira (₦ - million):</u>
Using sum of the year digits method and assuming that the residual/salvage value is 10% of initial purchase price;
Therefore residual salvage value is 10% of 50 million = 5 million
Depreciation in first year of operation = (50 - 5) x 20/210 = 4.3

Depreciation in second year of operation = (50 - 5) x 19/210 = 4.1 Total Depreciation over the two year period = 8.4 Value of Asset – Depreciation (50 – 8.4) = ₦ 41.6 million		
Other considerations pertinent to this analysis cont'd		
Year(s)	**Costs (₦ - million)**	**Benefits (₦ - million)**
1	Generators cost (Immediate payment), Electricity costs, Fuel costs and O&M costs	No benefits recorded
2	Electricity costs, Fuel costs and O&M costs	No benefits recorded
3	RES costs, Fuel costs and O&M costs	Money recouped from selling ½ diesel/petrol generators, savings on O&M, average savings on electricity and fuel costs
4 - 10	Electricity costs	Savings on O&M and average savings on electricity and fuel costs
8	RES component part re-installation	Savings on O&M and average savings on electricity and fuel costs

4.4.1. Scenario development

- Scenario 1: Represents a continuation of the current situation vis-à-vis grid connection, self-generation

- Scenario 2: It is assumed that improvements in grid reliability will allow for reduced reliance on self-generation with diesel

- Scenario 3: Complementing RES with diesel generation

4.4.2. Assumptions

- We created a single industrial electricity consumer, "Company X", which is based on the average load of the survey respondents, reflective of a typical industrial user in Nigeria. The following values were assumed in formulating the plant size, costs, demand profile and potential supply options for Company X.
- Industries having at least two operational generators with capacities and costs in the range of 150 kVA – 1250 kVA and ₦ 50 – ₦ 150 million respectively;
- Daily energy demand is 600 kWh, industries operate for 23 hours a day and demand is uniformly distributed throughout these hours i.e. 26.1 kW for each hour
- Scheduled maintenance of machineries and equipment occurring at least once every three months;
- With average cost of ₦ 50,000 for both generators maintenance i.e. ₦ 200,000 per year;

- Average monthly maintenance of 30 hours and grid power outage of 30 days per year;
- Increased number of outages as some residential consumers are served by sub-transmission lines;
- An 80% improvement in grid power (with good power quality) will bring about a reduction in self-generation and this will be reflected in the electricity and fuel costs – scenario 2;
- 220 kW is the amount of power required to sustain the industry's operation – scenario 3;
- 1500 m^2 is the estimated land space needed to generate this amount of power – scenario 3;
- Cost of the required land space using one of the industrial states in Nigeria (Ogun state) would be ₦ 25 million – scenario 3;
- System was sized with solar generation for 5 hrs a day and battery storage utilised for the remaining 18 hrs – scenario 3;
- Deep cycle batteries connected in an array with 50% depth of discharge were considered – scenario 3;
- Inverter and charge controllers having 10 year lifetime were considered – scenario 3;
- Renewable Energy System (RES) installation is 20% of capital cost – scenario 3;
- Batteries replacement every 5 years – scenario 3;
- Batteries re-installation cost in the 8th year is 10% of total purchase costs – scenario 3;
- Balance of System components (wires, switchgears, circuit breakers, connectors etc.) is 15% of capital cost – scenario 3;
- Annual maintenance of the RES is 3% of installation cost – scenario 3;

4.4.3. Scenario selection

The scenarios were selected to guide and refine the study's analysis. In painting a clear picture, the rationale was to present pessimistic, optimistic and pragmatic scenarios to better contextualise the study. Scenario 1 was the base scenario owing to the fact that it reflected the current reality of the economic sectors (industrial included) countrywide. It also represented the pessimistic scenario. Scenario 2 represented the optimistic scenario and was informed by the fact that the government were making efforts to significantly improve countrywide electrification. The 80% factor (from 2 hrs to 24 mins of outage per day) factor was to quantify “significant” improvement but at the same time highlight that improvements did not translate to achieving uninterrupted power supply. The final scenario was pragmatic and focussed on industries improving on their current electricity supply option i.e. Scenario 1 – grid power supply augmented by self-generation (diesel/petrol fuelled generators). It presented a pathway for total grid defection and security of supply (energy autonomy) for the industrial sector. The three scenarios selected were considered an adequate number to ensure the analysis was focussed and not unwieldy.

Two other possible scenarios were forgone in arriving at the three presented. One, depicted a current power system solution particular to Nigeria’s residential sector. It combines the grid power supply with self-generation. The self-generation configuration involves an energy storage system (ESS), an inverter and diesel/petrol generators. The set-up excludes the solar-PV element. It was forgone considering the scale of the sector studied and the practicality of scaling the solution to meet energy demand when deployed in an energy autonomous configuration. The other forgone scenario is predominantly deployed by the international oil companies (IOCs). They energise their operations from their exploration activities. Such a solution was considered out of scope for this study – owing to its economic implication and its peculiarity to the oil & gas sector.

4.5. Discussion

The cost benefit analysis of operating a manufacturing plant in Nigeria from the perspective of electrical power availability/unavailability has been undertaken. Average costs of fuel supply to diesel/petrol generators and grid power supply for the years 2014 and 2015 were calculated with the numbers derived forming an integral part of the calculations for all scenarios. The inflation rate for this purpose was set at 8.8% [33] with the discount rate at 14% [18]. The real discount rate taking into account inflation was calculated with a resulting value of 5% as shown in Table 4.9. The real discount rate was then employed in calculations to determine the present value of costs and benefits in the 10 year period. Certain costs due to their nature could not be determined and were not taken into account for these calculations. These costs, unlike the ones employed in calculations, vary per industry type, location, requirements, regulations and trade partners. Some of which include:

i. Cost of securing and extending dedicated 33 kV sub-transmission lines for factory use (costs determined by distance in kilometres);
ii. Cost of building an injection sub-station in cases where the factory is not located in an industrial area;
iii. Cost of procuring associated safety equipment – isolators and circuit breakers;
iv. Shipping and import duties on RES components;
v. Cost of transporting RES components to site.

Scenario 1

For this analysis, years 2014 and 2015 were considered the 1st and 2nd years of the 10 year period. The total costs incurred in the first year was the sum of purchasing; (2 × electric power generators), electricity costs, fuel costs and operation & maintenance (O&M) costs for the generators. The same costs were incurred in the second year with the exception of purchasing costs for the electric power generators (which was an immediate payment and only a factor for the 1st year). The 3rd – 10th year costs were constant and included electricity costs, fuel costs and O&M costs. Electricity costs and fuel costs for this period were chosen as the higher values of costs obtained for years 2014 and 2015 respectively, with O&M costs already defined in Table 4.9.

As this represents the current system of operations scenario, no benefits were recorded for the entire period.

$$(\frac{C}{1+i})t \tag{1}$$

$$(\frac{B}{1+i})t \tag{2}$$

Once the total costs were derived and populated in the table, equation (1) was used to determine the present value of the costs over the 10 year period as shown in Table 4.9.

Where; *C* = Costs; *B* = Benefits; *i* = discount/interest rate; *t* = years.

Thereafter, the total present values of costs were realised (as in Table 4.9) from the summation of present values of costs for the 10 year period considered. Therefore, the Net Present Value (NPV) for this scenario was a deficit of ₦ 1.898 billion.

Scenario 2

Years 1 and 2 are the same as in Scenario 1. The 3rd – 10th year costs assumed that electricity power supply would have become 80% more reliable and generator need was surplus to requirement or only available as security in the infrequent case of total grid system collapse. It is also assumed that an 80% improvement in grid power would bring the grid power outage days down to six. Thus the value for the 3rd to 10th year for both electricity and fuel costs were constant and was derived by calculating the total cost of electricity for 359 days and the cost of fuel for the remaining six days in the year (working with year 2 values). Therefore this study set the cost of 80% improvement in grid power supply per year to factories' operations at ₦ 141 million and fuel costs at ₦ 18 million.

In the case of benefits, no benefits were recorded in the 1st and 2nd year. Although as power became 80% more reliable in the 3rd year, cost savings from generator fuel costs, O&M costs of generators and monetary value realised from the sale of half of the electric power generator were recorded as benefits for the 3rd to 10th year. The 3rd year recorded the most benefits of the seven years due to the sale of one of the electric power generators. All other years only took into account the average cost savings realised from fuelling the generators and their maintenance. The calculated cost savings for factories were ₦ 72 million (to the nearest million). Also, in order to maintain security of supply in an extreme situation, only one of the generating sets was sold. To determine the asset's sale price, a two year depreciation value was calculated and deducted from the original asset purchase price as shown in Table

4.10. The drop in average electricity costs in 2015 from 2014 can be attributed to increased hours of electric power unavailability to factories in 2015, whilst the drop in average fuel costs within the same period can be attributed to improved customer-supplier relationship and/or varying price of fuel i.e. petrol being cheaper than diesel in Nigeria.

The total costs and benefits were derived and populated in the table as per scenario 1 using equations (1) and (2). Thereafter, the total present values of costs and benefits were realised from the summation of present values of costs and benefits for the 10 year period considered. The NPV for this scenario was a deficit of ₦ 994.1 million as calculated in Table 4.10.

Scenario 3

Years 1 and 2 remained the same as in previous scenarios. The 3rd year costs comprised mainly of the purchase and installation of the RES. O&M of the RES, maintenance and fuelling of half of the generators accounted for the rest of the costs in that year. The 4th to 10th years with the exception of the 8th year, incurred costs from the O&M of the RES and maintenance and fuelling of half of the generators. The 8th year in addition to these costs, incurred costs from the purchase and re-installation of new batteries for the RES.

Similar to the previous scenarios, no benefits were recorded in the 1st and 2nd years. The 3rd year brought in the most benefits as a result of the sale of half of the generators. Total benefits for that year came to the tune of ₦ 254.7 million (savings realised from sale of half of the generators combined with savings on electricity consumption and savings on fuel purchase and savings on O&M). The 4th to 10th year recorded the same benefits as the 3rd year (₦ 213.1 million) excluding money realised from the sale of half of the generators (₦ 41.6 million). Savings on electricity consumption were set at ₦ 141 million which was the constant cost for grid consumption (years 3 – 10) in scenario 1. Savings on fuel purchase were set at ₦ 72 million which were same as the constant savings realised for this commodity in scenario 2 (improvement in grid power).

The total costs and benefits were derived and populated in the table as per scenarios 1 and 2 using equations (1) and (2). Thereafter, the total present values of costs and benefits were realised from the summation of present values of costs and benefits for the 10 year period considered. The NPV for this scenario was savings to the tune of ₦ 594.8 million as calculated in Table 4.11. It is also important to note that this scenario was the only business viable scenario going by the numbers derived post analysis. Going by results derived from the analysis in Scenario 1, it is evident that factories are incurring significant costs to guarantee their power supply towards sustained operations. In Scenario 2, the situation improves with stable grid power supply and reduced dependency on electric power generators. These improvements in comparison to Scenario 1 (base scenario) led to significant savings to the tune of ₦ 905 million. Furthermore, the following points are elicited in summarising the analysis:

i. The current cost incurred by industries in the country due to lack of reliable grid power is significant and would unavoidably be transferred to the consumers in the sale price of commodities produced;
ii. Industries already incur various costs (safety equipment procurement, erecting substations, extending sub-transmission lines etc.) from liaising with TCN and DisCos in their coverage areas towards securing the longest possible hours of uninterrupted power supply;
iii. They also incur added costs from operating petrol/diesel generators towards securing their electricity supply as grid power failure is inevitably expected;
iv. On average, the reliance on diesel/petrol generators to industries' operations account for 40% of the total costs incurred in securing their electricity supply;
v. Savings of approximately ₦ 905 million per annum would be made if diesel/generators were less utilised and only available in cases of emergency power outage;
vi. From this study it is also questionable that total grid power with little or no dependency on the use of generators would be the best solution for reduced operations/production costs;

vii. Scenario 3 buttresses the latter point as “company X” recorded savings to the tune of ₦ 601 million per annum and further savings of ₦ 2.5 billion in comparison to base scenario;

viii. A situation where industries’ are in full control of their source of power generation (complementing a RES with diesel generator backup) seems the most plausible for increased profitability, sustainability for their business and favourable commodity price for the consumers;

ix. Also, knowing that diesel fuel emits 2.68 kg of CO_2 per litre consumption [39] with the cost of diesel per litre at ₦ 158 [22] and approximately ₦ 90 million is spent by industries on fuel per annum, 600,000 litres of diesel (1.61 kilo-tonnes of CO_2 gas) would be required to power generators and sustain operations in base scenario for “company X”.

x. Working with the best available data, the 126 industries we have on record in Ogun State (South-West) Nigeria, will emit 202.6 kilo-tonnes of CO_2 gas on average per annum into the atmosphere, thus contributing to human-induced climate change.

Figure 4.3 captures a snapshot of the implication of the results.

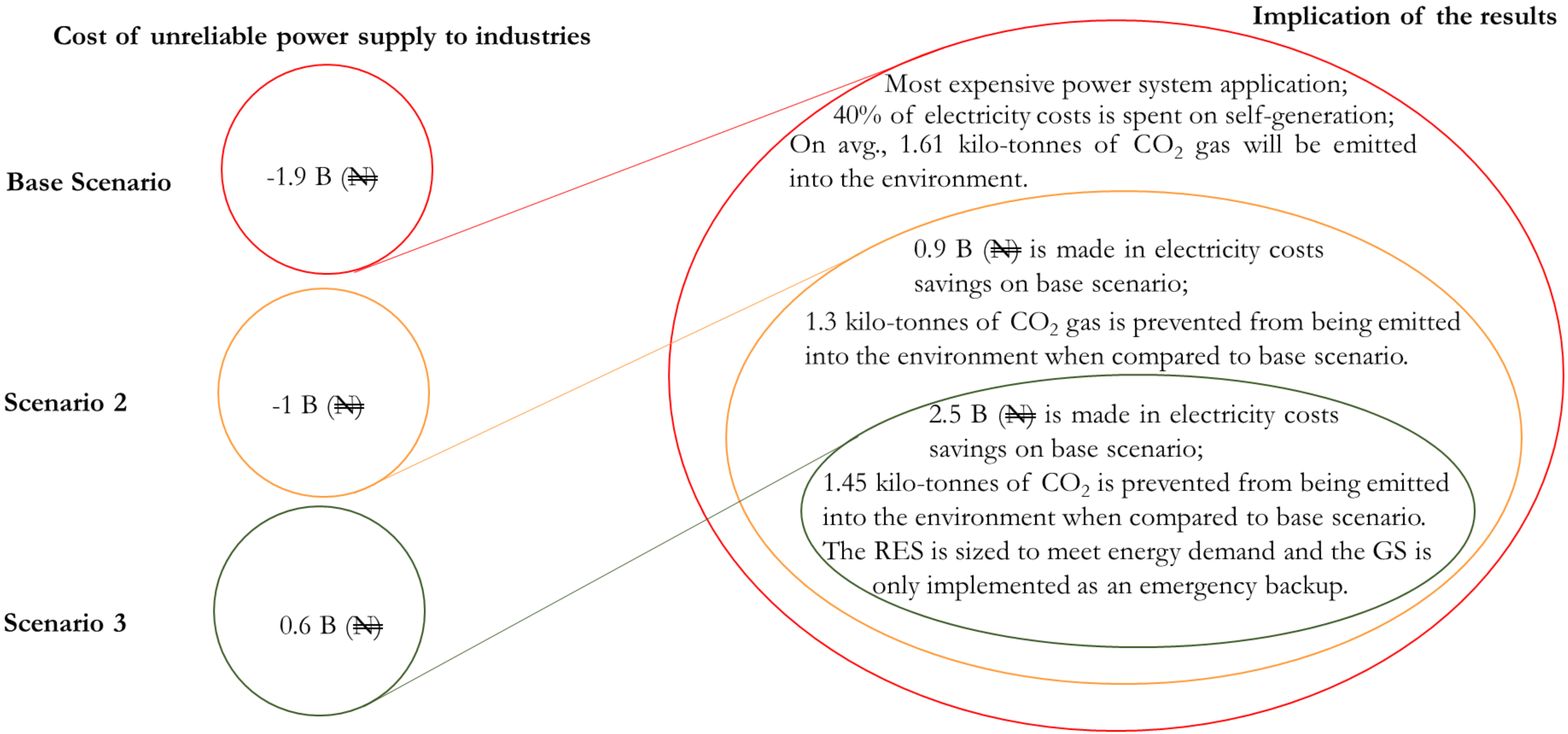


Figure 4.3 – Infographic on the implication of the results

4.6. Limitations

The limitations of the approach adopted for this study are:

- The range of activities and the disparateness in activities of the industries surveyed, meant that energy demand and by extension electricity costs would differ;
- Electricity costs for all but one geo-political zone (South-East) represented the cost data analysed in the study. The region that returned no analysable data i.e. the South-East, is considered a thriving location for industrial activities;
- Of the 20 industries NEMSA released data for, only 14 returned analysable data. In contrast, NEMSA's inspection portfolio covers in excess of 150 industries and industrial facilities;
- Dependence on secondary data sourced through other parties (NEMSA and GIZ) limited the qualitative data collection (questionnaire presentation, structure, information and content).

4.7. Conclusions

Post-privatisation Nigeria is still facing challenges that were existing prior to the electricity sector privatisation. The unbundling of NEPA although necessary, has not brought about the desired effects many expected. As the core departments of TCN (Transmission Service Provider (TSP), System Operator (SO) and Market Operator (MO)) strive to ensure improved service delivery to stakeholders and the wider nation, the Federal Government for its part must secure funding to accelerate the completion of integral ongoing projects countrywide. With the nation's operational generation capacity at approximately 3.9 GW and peak demand estimated at 12.8 GW (a shortfall of 70%), these roll out plans must be focussed and expedited to bridge the widening generation-demand gap, as well as meet electrification rate projection targets. It is critical that with the impending generation increase, there is measurable expansion in grid capacity to avoid the bottle neck that could present itself in operational generation capacity substantially exceeding the maximum wheeling capacity.

The case study in this paper revealed that a more cost-effective arrangement for the industrial sector is a hybrid system involving off-grid solar and diesel generation, as grid reliance complemented with diesel generation is cost-intensive and posed a problem to industry, sustainability and the respective cost of commodity and services to the consumers. Our results clearly show the huge cost incurred by Nigerian industry as a result of reliance on diesel generation. A typical industrial user would save ₦ 905 million per annum if grid reliability is greatly improved. However, distributed renewables may offer even greater cost savings of about ₦ 2.5 billion per annum, when adopted. Furthermore, this study found the last scenario the most affordable, reliable and sustainable of the three considered options. Cost savings of 132 % over base case scenario were recorded, with industries' ultimately becoming prosumers and securing their power supply as well as potentially decimating the 1.61 kilo-tonnes of greenhouse gas (GHG) emitted into the environment on average per year.

These results present a strong case for integrating renewable energy technologies for rural electrification, ensuring cost savings for industry, reducing countrywide GHG emissions, reduced reliance on imported hydrocarbons etc. Ongoing research on our part will focus on exploring and proposing appropriate methods for integrating renewable technology through software modelling and analysis with country-specific technical and resource data. Our research work will shift towards presenting the case for total to partial grid defection for the commercial sector in Nigeria. As solar photovoltaic offers the greatest potential to achieve these goals due to the abundant resource and excellent geographic distribution throughout the country, we will focus primarily on this renewable technology. Its integration into a hybrid mix similar to the case presented in this paper will be optimised for servicing variable load applications, especially those of commercial centres popularly referred to as plazas in Nigeria.

CHAPTER FIVE

Public awareness and societal acceptance of Renewable Energy in Nigeria

5.1. Introduction

This chapter acts as the intermediary between the problems created (through the lack of unreliable power supply in Nigeria) that were identified in the literature and chapter Four to the solutions presented in subsequent chapters. The interview of individuals representing the commercial, education and entertainment sector further elicited the impact of unreliable power supply to Nigeria. Consequently, a survey of Abuja city residents informed possible pathways to improving electrification in served communities, increasing electrification in underserved communities and extending electrification to unserved communities.

5.2. Interview definition – Impact of power supply on business operations in the multi-sectors

Three persons from different sectors that contribute to Nigeria's socioeconomic development were interviewed to determine the impact of electric power supply on their business operations. The commercial sector centres on a male in his 40's that has been running a barber salon business in a commercial centre (Mangal Plaza) in Abuja city for over 10 years. He runs a sole-proprietorship with no employees. The education sector centres on a female in her 60's that has been operating a private primary school in the suburban town of Kuje, Abuja for over 5 years. She has a workforce of approximately 15 employees and a total of 70 pupils. The entertainment sector focusses on a male in his 30's pursuing a career in the music industry in Lagos city for 7 years. He runs the business solely. The interview for the commercial sector was conducted over "WhatsApp" instant messaging and those of the education and entertainment sector over "WhatsApp" voice call. The interview questions and responses are detailed in Table 5.1. Questions are denoted as "Q", the commercial sector as "CS", education sector as "EDS" and entertainment sector as "ES".

Table 5.1 – Interviews on the impact of power supply on business operations in the multi-sectors

Q.1	How has your electricity supply impacted your business operations?
CS	*“Really, really bad. It has always been lights out and generator has always been the idea of running the business. Buying fuel to run your generator, and most times you waste fuel just to keep the place lively”*
EDS	*“Increased costs from augmenting the power supply with petrol generator to ensure well-lit classrooms, conducive environment and in sustaining e-learning through digital devices”*
ES	*“The electricity supply makes me schedule my music recordings and music production based on guesstimates of when supply would be available and when the generator can best be utilised”*
Q.2	What are your business’s top three running costs?
CS	*“Rent, light and working materials”*
EDS	*“Labour, electricity costs and miscellaneous”*
ES	*“Electricity costs and music software and hardware costs”*
Q.3	What steps have you taken to ensure security of electricity supply for your business operations?
CS	*“The use of solar is expensive and also inverters so we stick to just the generators and rechargeable clippers for now”*
EDS	*“Procuring, operating and maintaining a power generator”*
ES	*“Purchasing a power generator set and extra storage space and facilities for diesel fuel”*
Q.4	What is the average additional monthly cost of implementing the measures described in Q.3?
CS	*“Well, at most $50 a month”*
EDS	*“On average, $300 every month”*
ES	*“Generator capital cost – $500; Fuel – $30 and Maintenance – $65 every 3 months”*
Q.5	What direct impact has electricity supply had on services rendered and/or your business performance?
CS	*“Really terrible. To an extent you can’t use an air conditioner if you are running a generator or inverter or a solar system. So electricity is very vital and very essential in terms of running a closed door business like this”*
EDS	*“More fuel costs as we tend to utilise our generators more. Sometimes we go a week or two without electricity supply. Other times, we have to resort to business centres in producing necessary paperwork for the school. Transit times to and from these centres are business hours lost. Our business operations are hinged on constant electricity supply, for the fans, air-conditioners, typing exam questions, security lighting and facilitating digital learning”*
ES	*“It slows down my productivity and turnover of music records by double the normal time”*
Q.6	Rank the following terms from 1 to 3 in order of most preferred to least preferred, for your power supply system: • Affordability [ ] • Reliability [ ] • Sustainability[ ]
CS	*Reliability [1]* *Sustainability [2]* *Affordability [3]*
EDS	*Affordability [1]* *Reliability [2]* *Sustainability[3]*

ES	*Reliability [1]* *Sustainability [2]* *Affordability[3]*
Avg.	*Reliability [1]* *Affordability[2]* *Sustainability [2]*
Q.7	For the same cost and reliability would you prefer a grid-connected system or an independent sustainable energy system solution (with grid parity)?
CS	*"For me, I'll prefer an independent sustainable energy system solution"*
EDS	*" I prefer the independent sustainable energy system solution"*
ES	*" I would prefer the independent sustainable energy system solution"*
Q.8	Does unreliable electricity supply impact your quality of life away from work? If so, how?
CS	*"Yes it does. You won't be able to eat much when you have an uncovered responsibility to take care of. Your income determines your outcome. If you don't have much income, you can't spend much or else you'll crumble in your business"*
EDS	*"Yes it does. The stress levels has led to me experiencing recurrent headaches"*
ES	*"Yes, it does. It denies me the duration of sleep I would like to get as I have to work during unconventional hours"*

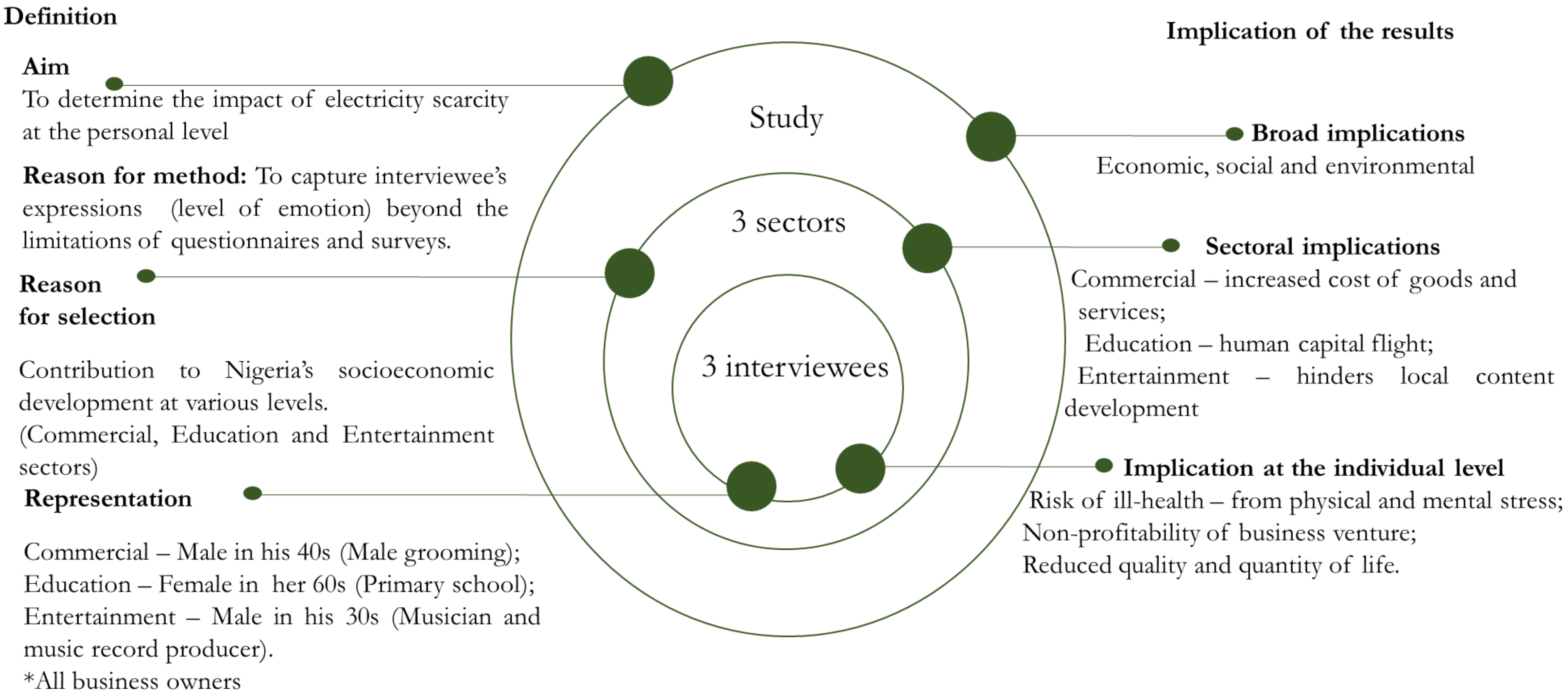
5.3. Interview findings

The electricity situation is a problem that all businesses share in common. The businesses interviewed identified electricity costs as one of their top three operational costs. The pervasive use of petrol or diesel generators in assuaging the impact of unreliable power supply was adopted across businesses. A level of knowledge on RET (particularly solar-PV) was observed. The "CS" interviewee referenced solar-PV technology as an alternative to grid power supply augmented by diesel/petrol generators. A struggle in articulating his understanding of the technology highlighted a need for further awareness on solar-PV's potential in power generating applications.

In quantifying the direct impact of electricity unreliability on services rendered or business performance, the "CS" interviewee complained about having to tolerate extreme weather for **extended hours**, as operating air-conditioners for the duration of his business hours was not viable. This affected his performance and in turn business productivity. A personal experience with the "CS" interviewee in 2015 centred on a planned haircut coinciding with a national fuel scarcity. His inability to procure gasoline for his power generator after three days of trying meant he lost my patronage (and possibly other potential customers) for that particular business period. The "EDS" interviewee's irritation arises from lost **business hours** transiting between the school and business centres on occasion. The “ES” interviewee highlighted the impact on his business productivity: *“It slows down my productivity and turnover of music records by* ***double*** *the* ***normal time****”*.

Businesses preferred reliability over affordability and sustainability as requirements for their power systems. Of the three requirements, reliability averaged at 1 with affordability and sustainability tied at 2. They also preferred autonomous power systems over grid connection if the former was at parity with the latter. In evaluating the impact of electricity unreliability on the business owners’ quality of life, the “CS” interviewee elicited the relationship between power supply, business profitability and mental health. With a countrywide lack of awareness on mental health [89], a sufferer could be stigmatised or improperly diagnosed further exacerbating the situation.

As business profitability impacts livelihood, falling short in projected financial gains could take its toll on mental and/or physical health [87]. The “EDS” and “ES” identified its impact as elevated stress levels from working in a non-conducive environment and not getting the required amount of sleep respectively. Elevated stress levels have also been identified to affect mental and physical health [87]. A vicious cycle is created with unreliable power supply also impacting the health sector’s efforts in providing quality health care services [88]. Figure 5.1 succinctly captures the social study undertaken here in an easy to follow graphic.



Definition

Aim
To determine the impact of electricity scarcity at the personal level

Reason for method: To capture interviewee's expressions (level of emotion) beyond the limitations of questionnaires and surveys.

Reason for selection

Contribution to Nigeria's socioeconomic development at various levels.
(Commercial, Education and Entertainment sectors)

Representation

Commercial – Male in his 40s (Male grooming);
Education – Female in her 60s (Primary school);
Entertainment – Male in his 30s (Musician and music record producer).
*All business owners

Implication of the results

Broad implications
Economic, social and environmental

Sectoral implications
Commercial – increased cost of goods and services;
Education – human capital flight;
Entertainment – hinders local content development

Implication at the individual level
Risk of ill-health – from physical and mental stress;
Non-profitability of business venture;
Reduced quality and quantity of life.

Figure 5.1 – Illustration of the implications of the results from the interview-driven social study

5.4. Survey presentation and analysis – Survey of Abuja city residents' energy usage and renewable energy awareness

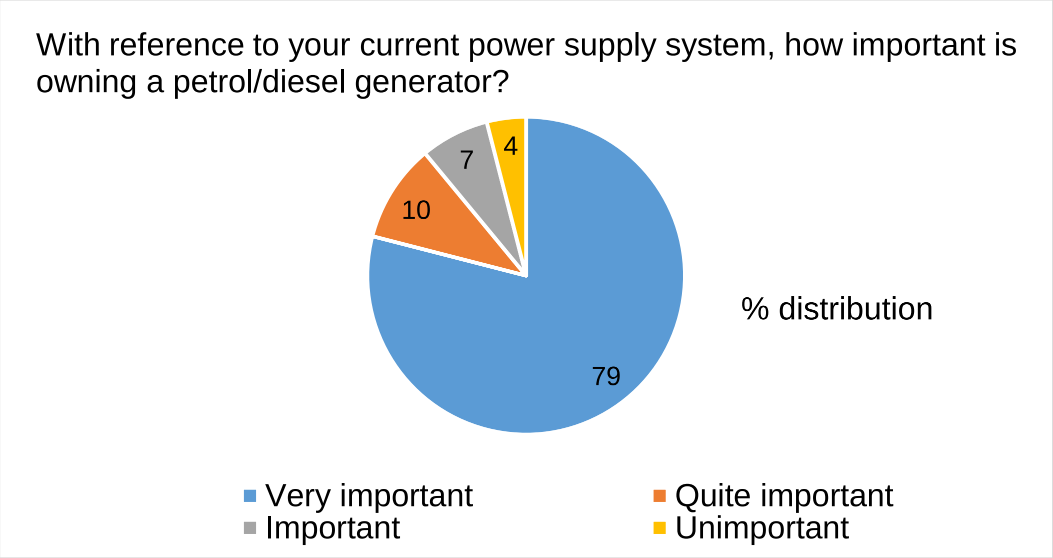
Abuja city residents were surveyed to determine their awareness and acceptance of RE, as well as to inform power system operations design consideration. Abuja, Nigeria's capital city was selected for the survey. Prominent factors in its selection were, the diversity of ethnicities resident in the city and its seat of power (political and legal) in the country. It was envisaged that results obtained using Abuja as the focal city would be replicable and/or adaptable for the broader Nigeria. Survey Monkey (an online survey development software) was used in the survey's creation, accessibility (URL link) and data analysis.

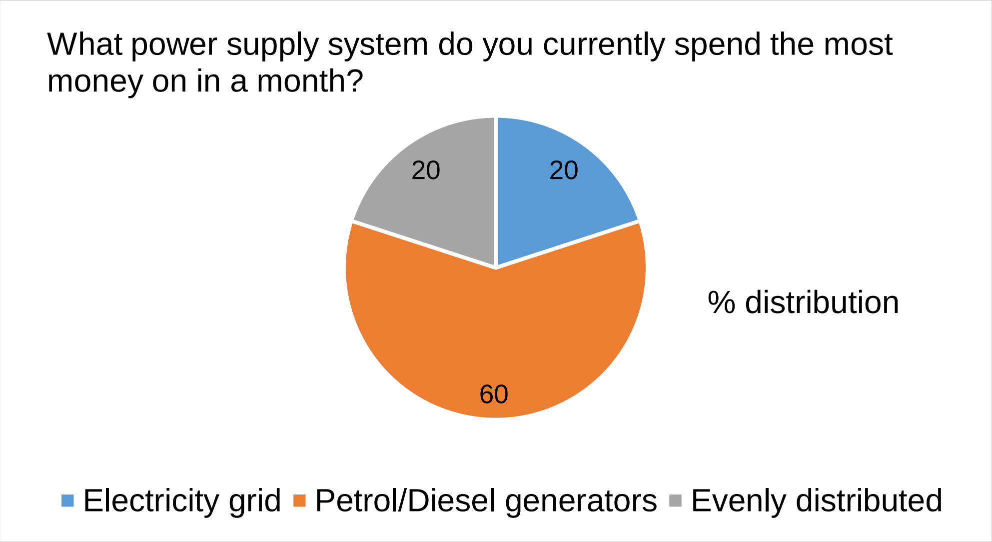
With a set target of 200 respondents, the survey was distributed via e-mail and SM platforms i.e. “WhatsApp” and “Instagram”. Selection of the sample size was guided by published tables in Israel's [25], and Bartlett *et al.'s* [26] papers. Social media platforms were employed for the survey distribution, due to their wide reach and ease of user access. The best representative data was obtained by keeping the survey's questionnaire concise for responsiveness, by not asking leading questions, and by avoiding the three and five-point response scale i.e. options of maybe, undecided, fair etc., for most questions.

The survey returned 233 responses for the mandatory questions, recording an average response rate of 98%. The optional and ranking questions returned 102 and 135 responses respectively. A response rate of 43% for the former and 57% for the latter. Table 5.2 shows a snapshot of the survey's questionnaire with a percentage analysis of respondents' answers. Figure 5.2 visually represents select data from Table 5.2.

Table 5.2 – Survey of Abuja city residents' energy usage and renewable energy awareness

S/N	**Question**	**Responses (respondents percentage distribution)**				**Total respondents**
1	With reference to your current electricity supply system, how important is owning a petrol/diesel generator?	Very important (79%)	Quite Important (10%)	Important (7%)	Unimportant (4%)	234
2	What power supply system do you currently spend more money on in a month?	Electric grid (20%)	Fuel/Diesel generators (60%)	Evenly distributed between both systems (20%)		235
3	Will access to a reliable electric power supply system encourage the disposal of your petrol/diesel generators?	Yes (82%)	Maybe (14%)	No (4%)		236
4	Are you familiar with renewable energy?	Yes (73%)	No (27%)			235
5	Name a few renewable energy sources (optional)	Solar (61%)	Wind (27%)	Biomass (12%)		102
6	Based on these options of renewable energy sources, which one do you think would take best advantage of Nigeria's climate/demographic/geographic location? Rank the options 1-4 (1 = most important; 4 = least important)	Wind Energy 1 (11%) 2 (20%) 3 (34%) 4 (35%)	Solar Energy 1 (66%) 2 (10%) 3 (6%) 4 (18%)	Biomass Energy 1 (12%) 2 (28%) 3 (25%) 4 (35%)	Hydro Power 1 (19%) 2 (41%) 3 (29%) 4 (11%)	1 (199) 2 (146) 3 (135) 4 (147)
7	Are you concerned about the environment?	Yes (93%)	Maybe (6%)	No (0.9%)	Don't care (0.4%)	235
8	What attributes are most important for your electric power system? Rank the options 1-3 (1 = most important; 3 = least important)	Reliability 1 (61%) 2 (19%) 3 (20%)	Sustainability 1 (28%) 2 (32%) 3 (40%)	Affordability 1 (29%) 2 (35%) 3 (36%)		1 (207) 2 (143) 3 (158)
9	If a renewable energy system was designed for reliability and sustainability to replace your current system; how much more will you be willing to pay over your current electricity costs?	0 – 25 % (45%)	25 – 50 % (35%)	50 – 75 % (14%)	75 – 100 % (6%)	233
10	Do you think an electric power supply mix that integrates more renewable energy sources will be pivotal in increasing countrywide electrification?	Yes (90%)	Maybe (8%)	No (2%)		234





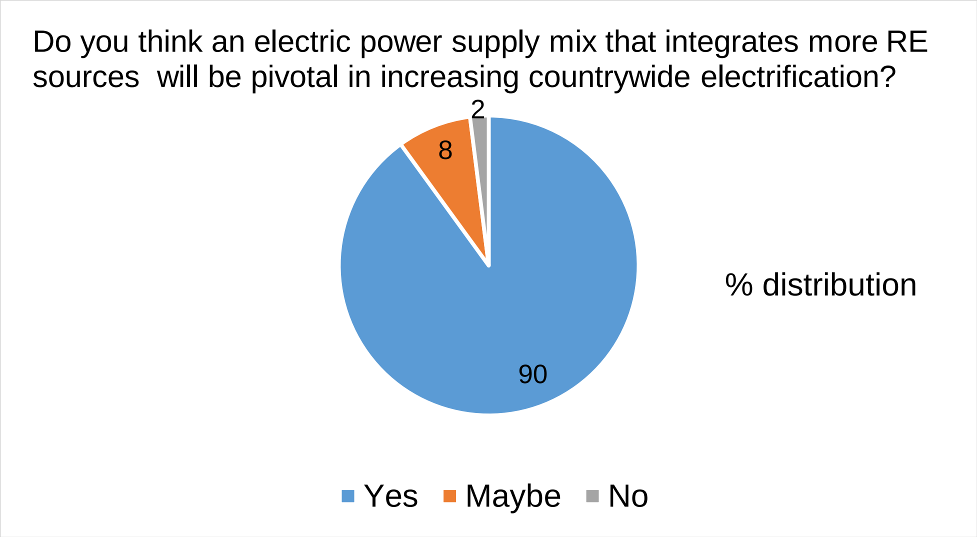


Figure 5.2 – Visual representation of select data from Table 5.2

Referring to published tables [25, 26] and with Abuja city having a population size greater than 100,000 [27], our sample size returned data precise to ±7% [25]. In other words, if 100% is the point of data accuracy the range of deviation of results was ±7% of that point. With regards to power system reliability, the survey results showed that 80% of respondents were willing to pay up to 50% more on their current electricity costs for improved reliability – an interesting highlight of the survey.

Completing the percentage distribution, 14% of respondents were willing to pay 50 – 75% more on their current electricity costs, with 6% willing to pay between 75 – 100% more. Another noteworthy result was 93% of respondents indicating concern for the environment but ranking affordability and reliability over sustainability as criteria/requirements for their power system. Less than 7.5% expressed indifference to environmental concerns. In surveying electricity consumers' power system requirements (What attributes are most important for your electric power system?), respondents ranked reliability, affordability and sustainability in descending order of importance. Table 5.3 details the breakdown.

Table 5.3 – Electricity consumers power system requirements assessed against the performance metrics of affordability, reliability and sustainability

Rank	**Performance Metric (respondents % distribution)**		
	Affordability	Reliability	Sustainability
1	29	61	28
2	35	19	32
3	36	20	40

Table 5.3 highlights electricity consumers' clear preference for reliable power systems over affordable and sustainable ones.

5.5. Survey findings

Solar power, as a RE resource, was the most popular amongst respondents and was also considered the most viable source of RE generation for the country. Furthermore, this survey identified reliability as the principal concern for electricity consumers, and provided power systems were reliable, consumers are willing to incur the added cost of implementing sustainable power systems. It further informed that electricity consumers will welcome sustainable power systems, provided they are reliable and are at cost parity or up to 50% more expensive than their current electricity costs (which are based on electricity grid supply plus generator systems). In light of these findings, it is hypothesised that a future proliferation of reliable power systems will drive electricity cost competition where affordability will return to the forefront as the primary driver for electric power systems.

5.6. Summary of social studies

The interviews conducted elicited the impact of power supply unreliability to the multi-sector (C&I, Education and Entertainment). In summary the impacts are lost business hours, increased generator usage, increased GHG emissions, increased electricity costs, reduced business revenue and reduced quality of life. Interviewees across the sectors preferred their power autonomy over dependence on grid power supply. Reliability and sustainability were favoured over affordability as power system requirements.

The surveys analysed corroborated interviewees inclination for their power system requirements. It also corroborated the impact of unreliable power supply to business operations. Solar-PV was the most popular RET amongst the interviewees and survey respondents, although, the interviewees and respondents evidenced little knowledge of its power generating potential. Limitations of the C&I, education, entertainment and health sectors were underscored by deficiencies in the power sector.

Isolating the education sector, a plummet in the quality of education either through its standard or delivery methods amongst other factors, particularly at the tertiary level are contributing factors to student migration [121]. These students on acquiring the requisite skills required to contribute towards a nation’s economic growth, development and transition might decide to stay on in the country of immigration (usually developed countries).

Canada estimates it is resident to 12,000 Nigerian students and Nigeria also ranked 4th, behind India, China and the Philippines in its 2019 list of economic migrants [120]. To a degree the social studies undertaken in this chapter, were able to link the deficiencies of the power sector to the socioeconomic status/performance of Nigeria.

By extension, the articles in [119-120] elicited a link between the socioeconomic status/performance of a country, economic migration and human capital flight (brain drain).

5.7. Justification of the methods adopted in conducting the social studies

The mixed methods approach adopted in conducting the social studies ensured the data extracted from the process were substantive. The aim of interviewing was to capture people’s expressions (level of emotion) beyond the limitations of questionnaires and surveys. The sectors interviewed were informed by their contribution to Nigeria’s socioeconomic development at various levels. As the industrial sector had been studied in Chapter Four, the commercial sector usually grouped in tandem with the former i.e. C&I, was selected primarily because the micro, small and medium enterprises (MSMEs) are the mainstay of an economy. The education sector was also selected because it is key to reducing illiteracy and producing the workforce that sustains economic activities. The entertainment sector was selected because it was one of the priority sectors identified by Nigeria in its economic growth and recovery plan (EGRP) [122].

By interviewing separate individuals, we were able to detail the direct impact of power supply unreliability to their businesses and quality of life i.e. the CS interviewee responded as quoted: *“Yes it does. You won’t be able to eat much when you have an uncovered responsibility to take care of. Your income determines your outcome. If you don’t have much income, you can’t spend much or else you’ll crumble in your business”*, to the impact of power supply on his quality of life post work. Whilst the impact of power supply unreliability would have an immediate effect on services rendered in the education and commercial (barbing salon) sector, its effect could be delayed in the entertainment sector (music making and production). Based on the representatives of these sectors, the effect of power supply unreliability on the education sector could also be immediately ameliorated i.e. revert to non-digital learning, without sourcing an alternative power supply option as opposed to the commercial sector.

The survey of the residential sector was undertaken to vary as well as supplement the interview approach. The aim of the survey was to generate widely quantifiable data that could not be achieved by interviewing. The sample size selection was guided by published studies on undertaking these types of analysis. The residential sector was selected because it housed the individuals that worked for all the other sectors that drive socioeconomic development. It was also viewed that the response from an individual could be representative of more than one individual in that household assuming it housed more than one person. Quantitative data was considered pivotal in informing the focal study in Chapter Six and solutions proffered in Chapters Six and Seven.

5.8. Limitations of the studies

Ideally, the face-to-face interview would have been the preferred interview technique, but as interviews were conducted during the COVID-19 pandemic, it was impossible to achieve this. This meant they had to be conducted remotely and the extent of information gathered was limited. Communication cost was a major determinant in the length and breadth (follow-up) of questioning, as well as in the duration of conversations (telephone and messaging). Network (connectivity issues) was another factor that tied into communication costs and affected the duration of conversations. As it was a semi-structured interview, the quality of information would have benefitted from a face-to-face interview. As facial expressions, vocal expressions (not readily captured in text/via phone calls) and body language would have been noticed and documented for further analysis post-interviewing. It would have also set the scene for follow-up questions to better elucidate the interviewees’ responses. Also the sample size selected to be interviewed was limited due to the cost of communication. A larger size of interviewees spanning more commercial businesses (cyber cafés, tailoring, grocery stores), across the levels of education (secondary and tertiary), and more independent players (musicians, producers, record label owners) in the entertainment industry would have improved the quality of data analysed. The limitations of the study on the results (or patterns identified in the study) is in the level of representation. The impact of unreliable power supply on a male grooming business (and its owner) in a particular commercial centre, may differ from a cyber café or tailoring business. It could also differ from another male grooming business (and owner) in a different commercial centre. The impact of unreliable power supply across the levels of education could also vary significantly (or insignificantly).

The survey method was intended to build on the data realised from interviewing, by presenting quantifiable data to buttress or contrast preliminary findings on the subject studied. In trying to ensure responsiveness, questionnaires had to be concise (maintain a structure) and certain questions from the interviews i.e. socioeconomic impact of unreliable power supply on individual and business operations, were not further investigated in the questionnaires for the survey. Furthermore, survey through SM only provided data from the residential sector. The intention was to conduct a field study focussing on commercial centres in Abuja, Nigeria. This was to be carried out in-person and through questionnaires manually distributed to business owners in commercial (40) centres in Abuja. The COVID-19 pandemic also disrupted the implementation of this approach. This meant that the study was limited to data realised form the survey of the residential sector. The potential implication of analysing results from the residential sector without comparing or contrasting with the commercial sector was the extent of representation and/or data validity. For example, power consumption patterns would differ due to the nature of the activities that characterise a residential building compared to a commercial setting. Employing the services of a statistician as highlighted in the review of the literature, could have helped in the application of the methods i.e. introducing survey instruments, towards improving data representation. This was forgone due to the onset of the pandemic and time constraints.

Although, given the limitations of these studies, the result analysed elicited to a degree, the problem of power supply unreliability in Nigeria and presented workable data that could be built upon in further studies. A study with a more social focus, could further explore the socioeconomic impact of unreliable power supply by assessing against other metrics such as quality and quantity of life (areas considered outside the scope of this research).

CHAPTER SIX

Practical solutions for increased electrification, lower emissions and lower energy costs in Nigeria

Preamble

The commercial sector in Nigeria, in terms of business operations, can be broken into structured, semi-structured and unstructured businesses. Structured businesses are the commercial activities carried out in a cohesive business environment (defined physical layout with seamless business units' interaction). Examples include major supermarkets, shopping malls and departmental stores. An example of a popular shopping mall in Abuja is shown in Figure 6.1.

Exterior view

Interior view

Figure 6.1 – Silverbird entertainment centre, Central Business District, Abuja, Nigeria, © 2018, Demilade Olowosejeje, used with permission.

Unstructured businesses are the commercial activities carried out in a business or trading environment with little or no distinct cohesion (undefined physical layout with interference in business elements/units' interaction). Examples include the central and local markets. An example of a popular market in Abuja is shown in Figure 6.2.

Exterior view

Interior view

Figure 6.2 – Wuse market, Wuse 2, Abuja, Nigeria, © 2018, Demilade Olowosejeje, used with permission

Semi-structured businesses have elements of both structured and unstructured businesses (defined physical layout with probable interference in business elements/units' interaction). Prime examples are commercial centres popularly referred to as shopping plazas or plazas. An example of a popular commercial centre in Abuja is shown in Figure 6.3.

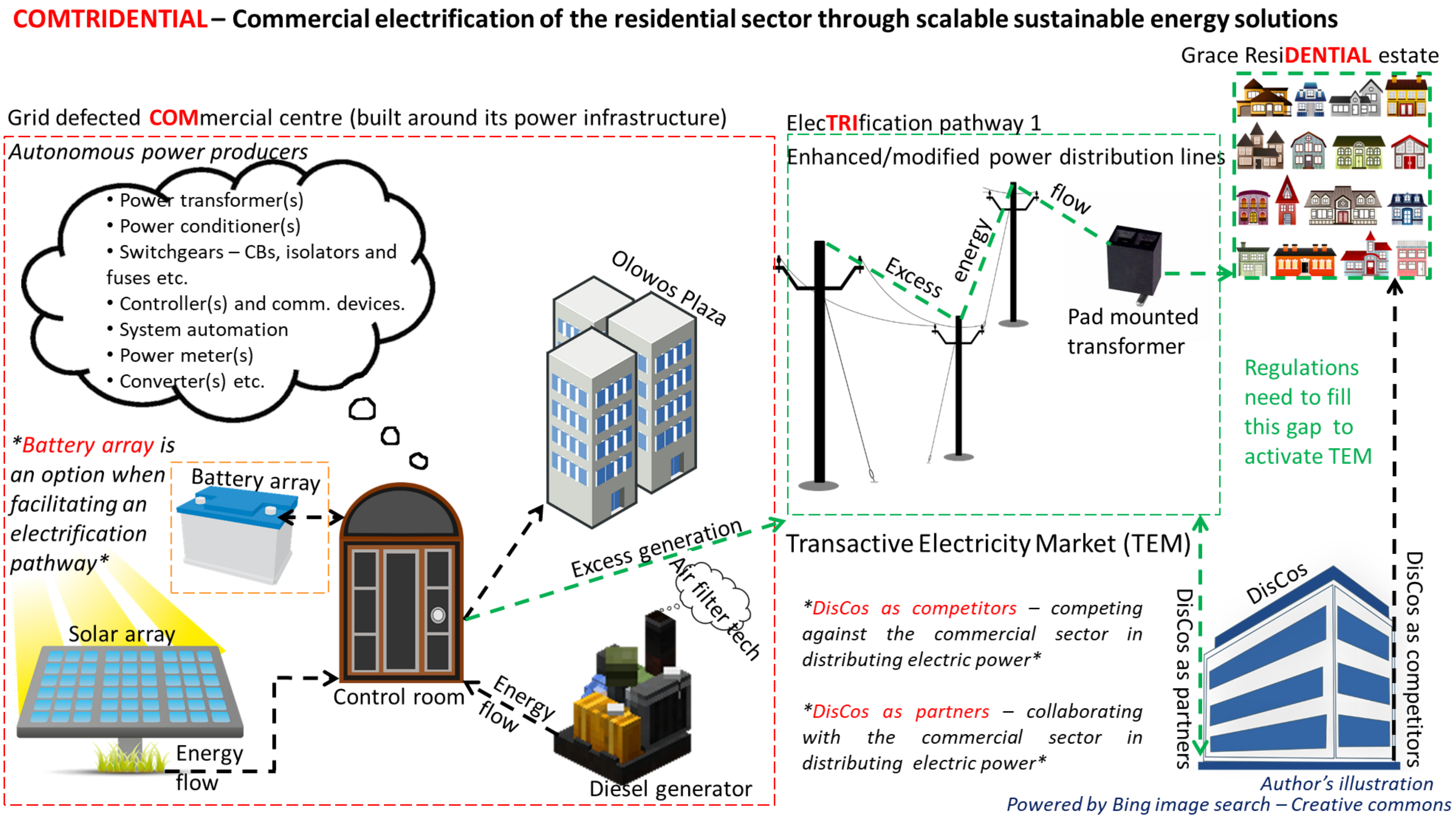
Exterior view *Interior view*

Figure 6.3 – Banex plaza, Wuse 2, Abuja, Nigeria, © 2018, Demilade Olowosejeje, used with permission

These commercial centres are available countrywide and are located in commercial areas with a few sporadically dispersed in residential areas. They have a standing consistency in their commercial activities and are built to accommodate a range of businesses. Some of these activities include: the sale of materials and clothing; sales of groceries; sale of consumer electronics; to rendering commercial services such as; tailoring, beauty and cosmetic grooming, and cyber café operations. These centres usually accommodate more than one provider of the same commercial activity and are also known to house businesses that offer professional services such as; legal and engineering consultancies. Although a rarity, not-for-profit organisations like religious institutions can be found in commercial centres.

With the Federal Government intensifying efforts to cut its economic dependence on the oil sector due to falling global prices [23], the commercial and industrial sectors can be positioned to become significant players/contributors to the nation's economy, following years of sectoral neglect [24]. This can be made possible by ensuring the resiliency and sustainability (e.g. use of low-carbon technologies) of their power supply systems. The commercial sector, unlike the industrial sector encompasses a very wide range of different commercial activities making the commercial space more exploitable. Integral to optimal operations and performance in this sector is the availability and accessibility to a safe, secure, and uninterrupted source of power supply. Considering these, it is imperative that a reliable, affordable and sustainable power supply system is deployed in energising and meeting the load demand of commercial centres in Nigeria. This chapter will analyse the integration of solar-PV in different power system configurations towards servicing variable load applications, particularly those of commercial centres popularly referred to as plazas in Nigeria**.**

Also, "Comtridential" the base electrification pathway proffered as a solution to increasing countrywide electrification in chapter Six, is represented. Comtridential, is an electrification pathway facilitated by the development of a transactive electricity market that explores the electrification of the residential sector through excess generation from hybrid renewable energy systems (HRESs) implemented for the commercial sector. Figure 6.4 is a representation of the implementation of this integrated power system solution for commercial centres in Nigeria**.**


COMTRIDENTIAL – Commercial electrification of the residential sector through scalable sustainable energy solutions

DisCos as competitors – competing against the commercial sector in distributing electric power

DisCos as partners – collaborating with the commercial sector in distributing electric power

Figure 6.4 – Commercial pathway to increasing countrywide electrification

A significant portion of this chapter is from the paper –A practical approach for increased electrification, lower emissions and lower energy costs in Africa. Sustainable Futures. 2, pp. 1 – 10. https://doi.org/10.1016/j.sftr.2020.100022

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Abstract

The limited access to affordable, reliable and sustainable energy in sub-Saharan Africa could inhibit the realisation of the United Nations sustainable development goals by 2030. The intermittency and unreliability of power supply in the region has led countries, especially in the eastern sub-region, to implement sustainable energy solutions for rural electrification, thereby improving electricity supply access to underserved and unserved communities. With this focus on rural electrification, a deficit in electricity supply to urban settlements could arise, owing to the economic feasibility of extending the power grid towards securing electricity access for a growing population and the increasing number of rural-urban migrators.

This paper reviews existing literature on electrifying sub-Saharan Africa, highlighting the prescriptions for deploying energy solutions in the region. Consequently, a country-level case study on grid defection solutions for Nigerian commercial centres assessing 14 different Integrated Power Systems' (IPS) operations against the three impact metrics of cost implication ($/lifetime), greenhouse gas (GHG) emissions (CO_2 tonnes/yr.) and surplus energy (MWh/yr.), is presented. The systematic analysis demonstrates that an integrated hybrid-solar-photovoltaics (PV)-based system (IHSS) without battery storage, serving 56% of its load from solar-PV and 44% from fossil fuelled generators provides the lowest cost power supply option. The modelled system generated 25 MWh/yr. in surplus energy and emitted 53% fewer GHG emissions than the largest emitter. A compelling case is made whereby augmenting existing infrastructure with an appropriately sized PV plant will significantly reduce costs and simultaneously have a significant impact on GHG emissions. The generation of surplus energy also presents an opportunity to augment urban electrification through custom-fit sustainable energy solutions and the formation of a transactive electricity market.

Keywords: beneficial electrification; economic cost; GHG emissions; grid defection; sustainable solutions; urban electrification

6.1. Introduction

Sub-Saharan Africa's (SSAs) electric power supply-to-demand shortfall has been widely documented [40, 41, 42]. The electrification rate of most countries in SSA excluding South-Africa is less than 30% with an average electrification rate of 16% in rural communities [42]. The paucity of electricity supply in the region is quite alarming, with the World Bank estimating that over 50% of the 1 billion people without access to electricity reside in SSA [41, 42]. Consequently, over 70% of primary energy is sourced from traditional biomass (fuelwood and charcoal), with more than half of SSA's electricity generated from large hydropower [43].

In the eastern sub-region, electricity consumption in 2015 for the EA-8 (Burundi, Kenya, Malawi, Mozambique, Rwanda, Tanzania, Uganda including South-Africa) stood at 261 TWh, with South-Africa consuming 227 TWh of the total figure [44]. In comparison, Italy consumed 310 TWh within the same period, despite having a fifth of the EA-8's total population [44]. At the country-level, Nigeria – the most populous nation on the continent still has to electrify over half its population [8] and improve the quality of power delivered to electrified areas. According to the World Bank, Nigerians with power supply access experience 33 power outages a month at an average outage duration of 8 hours [41]. The need for reliable power has resulted in the proliferation of small-medium scale fossil fuel generators of different models and capacities, giving rise to electricity costs and air pollution in the multi-sectors (commercial, industrial and residential) [45, 46]. The region's limited access to an affordable, reliable and sustainable source of power has inhibited its socioeconomic development, with attendant consequences on quality of life, public health, climate change, economic growth and prosperity.

Public health in SSA is of concern on two fronts: in rural communities and settlements where indoor pollution is a growing problem, with 65% of primary energy (cooking, heating and lightning) in the EA-8 sourced from solid biomass [44], and in urban regions where diesel/petrol fuelled generators are employed in ameliorating the effect of electric power supply unreliability on the quality of life. The air quality impacts from both situations could adversely impact human health [44, 47, 58, 63]. SSA's electricity crisis presents an opportunity to address the electricity access deficit in tandem with climate change. The region is already considered a non-significant contributor to global greenhouse gas (GHG) emissions with its global contributions at 2 – 3% attributed to energy related and industrial activities [48]. Furthermore, about 60% of the countries on the continent have committed to climate change mitigation by ratifying the “Paris Climate Accord” [40, 49]. However, South-Africa with an electrification rate of approximately 88% is looking to bring about 12 GW of coal-powered plants online, with Malawi and Zimbabwe also making considerable investments in coal-power generation capacities [42].

Climate policies and an enabling regulatory environment will be required in realising country-level and regional climate change mitigation commitments. The transition to a low-carbon economy has garnered some level of success in the eastern sub-region [16], with countries implementing sustainable energy solutions for rural electrification [42]. A notable industry leader in SSA is M-Kopa – a Kenyan solar energy company, serving Kenya, Tanzania and Uganda. According to the company, they have been able to develop solar home systems (SHSs) for over 600,000 low-income households in these countries, providing them with affordable and cleaner access to energy [50]. They have also been able to pioneer a pay-as-you-go mobile payment system for collecting returns on their services and in remotely monitoring (communicating with) their physical asset.

As the discourse on SSA’s electricity paucity centres on providing electricity supply access to underserved and unserved communities particularly in rural areas, urban regions could experience an electricity supply deficit resulting from natural population growth and rural-urban migration. With over 50% of the African population predicted to be living in cities by 2030 and 60% by 2050, urbanisation is a social phenomenon that could influence access to electricity by putting pressure on energy resources and infrastructure [42]. At the country-level, Nigeria is predicted to add about 212 million people to its urban population between 2014 and 2050 [40]. The success recorded so far through the deployment of low-carbon technology for rural electrification in eastern Africa, presents an opportunity for exploring sustainable energy solutions in extending power supply access, improving power quality and sustaining the duration of electricity supply to a growing urban region (commercial, industrial and residential) in SSA.

In light of these conditions, further discussions in this paper are structured as follows: Section 6.2 covers a review of the literature on the energy solutions and drivers to energy access in SSA. Section 6.3 presents the method, outlining the case study on Nigerian commercial centres and defining system operations design. Section 6.4 covers the results of the case study analysis with Section 6.5 discussing the implications of the results. Section 6.6 concludes the paper.

6.2. Review of relevant studies

The literature on SSA's electricity supply paucity and the energy solutions that could bridge the power supply to demand deficit is extensive, with discussions highlighting power supply access and reliability as a nexus to the region's socioeconomic development. Documented energy solutions for electrifying SSA's unserved and underserved communities favour sustainable energy solutions due to their minimal to zero adverse impact on public health and the environment, among other factors. Consequently, literature on SSA's electric power supply unreliability is reviewed accounting for the western, eastern and southern Africa sub-regions, with discussions split into energy solutions for increasing electrification and the drivers for improving electricity supply access.

6.2.1. Energy solutions

With the electrification rate of most countries in SSA excluding South-Africa below 30% and an average electrification rate of 16% in rural communities [42], existing literature on energy solutions for the region mainly focus on implementing sustainable solutions for rural settlements towards meeting their primary energy needs i.e. cooking, heating and lighting. Okoye and Oranekwu-Okoye [52] advocated the economic viability of solar-PV systems for rural electrification in SSA, using rural Gusau, Nigeria as a case study. Other studies by Azimoh *et al.* [61] on rural Namibia and Boamah and Rothfub [57] on Ghana analysed the successes of the hybrid (solar-diesel) mini-grid system in operation and the government led solar home system (SHS) initiative respectively. Considering the wider benefits of “electrification beyond lighting”, Schwerhoff and Sy [58] identified large-scale renewable energy developmental projects requiring substantial capital as integral to electrifying SSA and accelerating the transition to sustainable energy solutions. Barasa *et al.* [59] demonstrated the cost suitability of renewable energy (RE) systems delivering power through a high voltage direct current (HVDC) grid and their potential in increasing regional electrification through interconnected grid systems. Presley *et al.* [51] disputed the immediate focus on deploying sustainable solutions for electrification by arguing that the transition should only occur once conventional energy has been scaled up and utilised in achieving the “benchmark” of reducing energy poverty and accelerating economic growth and development. Adhekpukoli [66] presented the democratization of Nigeria’s electricity industry by further deregulating the sector to accommodate disparate electric power producers as a solution to the ‘decades-long’ electricity supply deficit. There is a need for sharing the emphasis on Africa’s electrification agenda between the rural deficient and increasing electricity supply access to urban regions, particularly economic drivers like the commercial and industrial (C&I) sectors. A cost-benefit analysis by Olowosejeje *et al.* [1] on Nigeria’s industrial sector realised that industries could make significant cost savings if they transitioned to solar-PV based systems instead of complementing unreliable grid power with diesel generation. Sustainable energy solutions are being favoured for narrowing the electricity supply shortfall in rural SSA because they address the global issue of climate change. Chakamera and Alagidede [54] emphasized the need to mitigate the adverse effect of climate change by decreasing electricity production from non-renewable energy sources and increasing production from renewable energy sources in the long term. Ouedraogo [55] stated that the economic, social and environmental benefits of deploying renewable energy technology and infrastructure outweighed its capital-intensive nature.

Rose *et al.* [72] evaluated the potential of solar-PV (combined with reservoir hydropower) grid connected systems in displacing diesel generation in Kenya. They suggested that these large scale RE systems are more impactful investments in providing sustainable energy solutions and significantly reducing carbon emissions.

The United Nations 2030 target of ensuring access to affordable, reliable, sustainable and modern energy for all might have to be revised due to the rate at which SSA is being electrified. To support this point, Bazilian *et al.* [60] considered regional electrification targets in line with that of the sustainable development goals (SDGs) as quite ambitious, stating that power generation capacity has not kept pace with population growth. They also put forward the contrasting level of commitment to power development projects among countries in the region as a significant issue in realising the SDGs within the stipulated time period**.**

6.2.2. Energy access drivers

The unavailability of and inaccessibility to data on the energy sector in SSA critically inhibits effective electricity supply planning and implementation. Trotter *et al.* [53] identified a major problem of electricity planning as the lack and unreliability of data. Simone and Bazilian [62] in discussing the role of international institutions in fostering SSA's electrification, implored the establishment of an information sharing mechanism towards improving the delivery of financial instruments and initiatives to the region. Ateba and Prinsloo [70] in identifying an effective approach towards electricity supply sustainability in South Africa, recommended the development of an integrated strategic management framework for sectoral planning informed by the holistic and comprehensive analyses of grid operations. The necessity for accessible energy data cannot be over emphasized as energy policies are informed by available data on the production, distribution and consumption of energy. Trotter *et al.* [53] listed the enabling factors for sustaining SSA's electrification drive as adequate policy design, sufficient finance, securing social benefits, a favourable political situation, community engagement together with human capital development. Azimoh *et al.* [61] listed government support, involvement of the local community, capacity development of same, sensitisation towards energy efficient practices, prepaid metering and the adoption of a progressive electricity tariff system as factors that have sustained the operation of the mini-grid system in Tsumkwe village, Namibia. In another study, Jain and Jain [69] presented political instability, contrasting energy strategies, technical ineptitude and grid infrastructure modification/integration as issues to be addressed in electrifying rural localities through renewable energy technology (RET). Adesanya and Schelly [63] concluded that renewable energy uptake in Nigeria is subject to supporting energy policies and an awareness drive through synergies amongst the government, financial institutions, private investors and stakeholders.

It is imperative that the renewable energy industry in SSA is de-risked to promote investments in renewable energy technology (RET) by private investors, multilateral financial organisations and international development partners. Obeng-Darko [65] in discussing the impeding factors to Ghana utilising renewable energy and energy efficient technologies in achieving a 10% penetration of national electricity production by 2020, highlighted deficiencies in legislative and regulatory frameworks as risk escalators deterring investments in renewable energy development projects and initiatives. Consolidating discussions in [65], Aliyu *et al.* [67] highlighted the importance of renewable energy policy mechanisms such as; feed-in-tariffs and net energy metering in promoting and incentivising investments in renewable energy technology. Moner-Girona *et al.* [71] recommended the implementation of RET-specific tariffs for incentivising national and international investments in RETs. Social factors and societal behaviours have to be considered in the deployment of energy solutions and more particularly innovative solutions and new technology. Boamah and Rothfub [57] stated that the interrelationship between energy and society is an important factor in implementing energy development projects. Wojuola and Alant [64] inferred the integration of sustainable development in education, science and technology policies towards fostering a national sustainable development culture, after realising a low-level of knowledge on RETs in their survey of Ibadan, Nigeria. They also recommended that energy education encompasses all knowledge delivery systems. Misplacing priorities on energy development projects could scupper the rate at which continent-wide social and economic development is achieved. Trotter and Abdullah [56] proposed that international involvement in Africa’s energy sector be redirected towards focussing on making public aid available for rural electrification, promoting local content through dissemination of technology and relaxing the conditions on foreign-aid in order to support state-driven leadership. Simone and Bazilian [62] also proposed that international institutions channel their efforts into supporting the development of sound energy policies, sectoral reforms, corporate governance and ensuring transparency best practices. Renewably-powered systems for rural electrification could be faced with sustainability challenges, if the after-services are not functional. Azimoh *et al.* [68] surveyed rural households in South Africa to investigate the impact of the SHS program on the community. They argued that although the program had facilitated the illumination of households increasing study and business hours, it was not sustainable in the offing due to the inadequacies of the fee for service payment model, the system's limited power supply, improper system use, equipment theft and the rising cost of doing business for the energy service companies.

6.2.3. The gaps in the literature

A review of the literature shows solar-power based systems as the preferred energy solution (due to a continent-wide resource abundance) in facilitating SSA's electrification. Their deployment either in stand-alone configurations or in complementarity with fossil fuel based systems were consistent in the discourse. Also consistent in the literature was the mode in which these RETs were implemented (SHSs and mini-grid systems).

Following the extensive literature review, we present three stages/enablers to energy supply access. The first stage encompasses a politically stable environment, reliable data that is readily accessible and energy policies, with policy actions supported by an enabling legislative and regulatory infrastructure. Access to RE development finance, mechanisms incentivising RET investments, dissemination of RET, energy sector reforms and effective payment models for collecting returns on RET services constitute the second stage. The third stage focusses on community engagement in determining the best-fit innovative solutions as well as in inculcating a community-wide technology sustenance culture post-project implementation. The first stage serves as the building blocks for the successful implementation of the second stage with the final stage ensuring the sustenance of the project after completion.

Throughout the breadth of the literature, discussions have centred on implementing grid defection solutions (small-scale SHSs and mini-grid systems) for the electrification of rural SSA. With an electrification rate of less than 30% in most SSA countries [42], it is important that electrifying rural areas is in tandem with extending and improving the quality of power delivered to urban regions. It is also important that electrification goes beyond lighting and provides the quality of power required in meeting the operational demands of urban-domiciled commercial centres and industries. This study seeks to address this gap in literature by analysing the economic and environmental viability of hybrid scalable solar-centric grid defection solutions for urban commercial centres (with urban regions comprising of commercial, industrial and residential sectors) towards a collective electrification drive i.e. increasing urban electrification and sustaining rural electrification efforts. A systematic analysis is carried out on 14 stand-alone integrated power systems in meeting the electricity demand of urban commercial sectors and by extension, augmenting electricity supply access to the residential sector. There is an opportunity for surplus energy generated from these hybrid systems to power the residential sectors through industrial and commercial coalition formations. As a sustainable approach in terms of economic viability, the non-essentiality of energy storage systems in these hybrid configurations based on regional location is also elicited. Focus on the commercial sector stems from the fact that small and medium scale enterprises are the mainstay of an economy.

6.3. Method

This study was guided by three fundamental pillars: affordability, reliability and sustainability. Commercial centres in Abuja's (Nigeria) metropolis were surveyed to establish their most commonly-occurring commercial activities, which informed load demand projections. Subsequently, Olowos Plaza, a model single commercial centre housing the commercial outlets that cater to these activities was created and modelled in detail as a case study. A systematic analysis was performed on 14 different integrated power systems (IPSs): (a renewable energy system (RES); a fossil fuel generator system (GS); an integrated hybrid solar-based system (IHSS); eight integrated hybrid solar and battery-based systems (IHSBS); and three integrated hybrid generator-based systems (IHGS)). A systematic approach was taken whereby the commercial centre's energy demand, the power systems selection, the power systems configurations and operations analysis were methodically designed and evaluated. The load profile of the commercial centre (extrapolated for a year) was determined, and thereafter power systems were integrated/configured based on their operational characteristics (depth of discharge, frequency of component part replacement, frequency of maintenance and diesel/petrol refuelling etc.). The systems operations were analysed to ensure they meet the centre's energy demand uninterrupted. The commercial centre's weekly load was quantitatively deduced from the power requirement of the electronic devices/equipment used in the centre. Initially 12 IPSs were selected i.e. two reference systems (RES and GS) and 10 hybrid systems that combined the reference systems in different capacities (and configurations). During the course of the operations design, two other systems were introduced i.e. IHGS 2 and 3. The rationale was to extend the range of power systems considered. These systems (IHGS 1, 2 and 3) were differentiated by substituting the order of their hybrid configuration(s). The capacity of the two reference power systems were determined first. The capacity sizing was based on their ability to independently meet the commercial centre's energy demand. Thereafter, power systems were populated within the range of the reference systems capacities. Designing the hybrid configurations for performance was based on an understanding/experience of power systems operation in service (especially for the diesel and petrol generators). In realising a viable solution, the power systems were analysed against three impact/performance metrics: cost implication ($/lifetime (20 years)), GHG emissions (CO_2 tonnes/yr.) and surplus energy (MWh/yr.). Table 6.1 summarizes the system capacities of the 14 IPS' operations designs.

Table 6.1 – Summary of the IPS' system capacities

IPS	Capacity (kW)			Capacity (kWh)
	Solar-Photovoltaic (PV)	Diesel Generator (DG)	Petrol Generator (PG)	Battery Array
RES	100	-	-	82
GS	-	15.5	2.2	-
IHSS	30	15.5	2.2	-
IHSBS 1	20	15.5	-	12
IHSBS 2	30	15.5	-	12
IHSBS 3	40	15.5	-	12
IHSBS 4	50	15.5	-	12
IHSBS 5	60	15.5	-	28
IHSBS 6	70	15.5	-	42
IHSBS 7	80	15.5	-	42
IHSBS 8	90	15.5	-	42
IHGS 1	10	15.5	2.2	-
IHGS 2	10	15.5	2.2	12
IHGS 3	10	15.5	-	12

6.3.1. Survey on commercial centres

Forty commercial centres in Abuja were surveyed to establish the most commonly-occurring commercial activities in these centres. A checklist was designed with 31 out of the 40 centres surveyed accommodating commercial outlets that engage in three or more of its listed activities, namely: cyber café businesses, boutiques, salons, tailoring businesses and grocery shops. These results informed the creation of Olowos Plaza, located in Abuja and housing a cyber café, boutique, salon, tailoring and grocery shop. See Appendix One for the survey checklist.

6.3.1.1. Load demand projection/determination

The weekly load demand of Olowos Plaza was realised based on the power requirements of the five commercial outlets. Olowos Plaza is open for business seven days a week with reduced business hours on Sundays. Some commercial outlets (cyber café, boutique and tailoring shops) are not operational on Sundays. Business operations are from 9am to 10pm, Mondays to Saturdays, and from noon to 5pm on Sundays. Business times are representative of most commercial centres in Nigeria. Figure 6.5 indicates the hourly load demand (kW) for Olowos plaza for a typical weekday, Saturday and Sunday. See Appendix Two, Three and Four for the typical week (weekdays and weekend) power consumption breakdown, equipment model and power rating, as well as business operation assumptions.

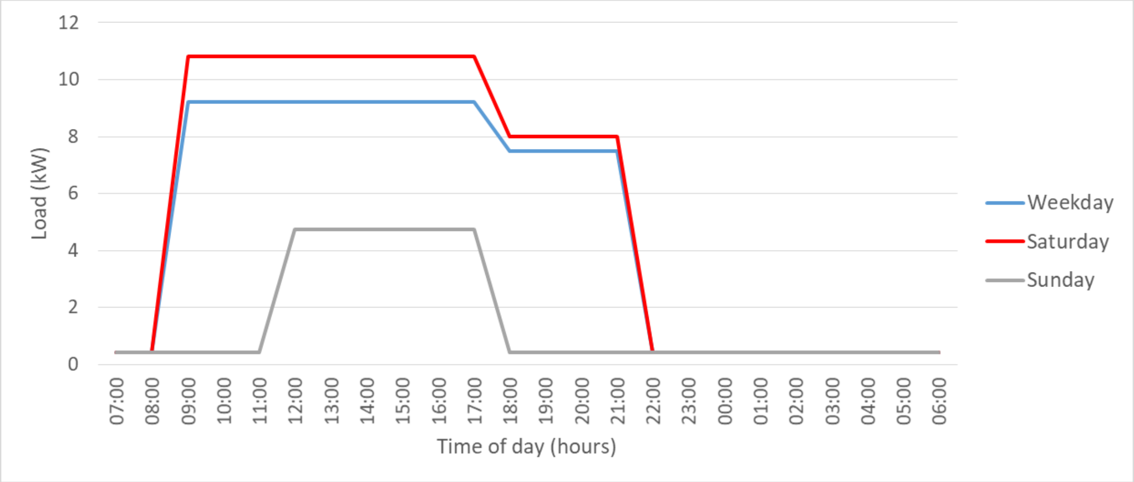


Figure 6.5 – Olowos plaza hourly load demand for a typical weekday, Saturday and Sunday

6.3.2. Power system selection and cost consideration

The three main power system components (although with different system compositions, and in different capacities and operations configuration) analysed in meeting Olowos Plaza’s load demand were a solar-photovoltaic (PV) system, a battery storage system and a fossil fuel generator system.

6.3.2.1. Solar-PV system

The Solar-PV system operations was designed using Abuja’s global horizontal irradiation (GHI) data for year 2017 sourced from Copernicus Atmosphere Monitoring Service [73]. 100Wp (Voc – 22.3V; Isc – 6A; Vmp – 18V; Imp – 5.56A; η – 19.2%) monocrystalline solar-PV panels (considering the technical data specific to the panel’s power rating) were selected and sized for every 10kW capacity increment, for systems’ operation design in the 10 kWp – 100 kWp capacity range. For practicality, “48 V” string array configurations were considered i.e. to limit the systems’ current-carrying capacity, thereby limiting the systems’ protection sizing. Determining the land size (surface area) the study took into account the solar constant (kWh/m^2), the PV module(s) power conversion efficiency (%) and the total PV system capacity size (kW). In determining the solar-PV energy produced per hour, the study took into account the aforementioned with the inclusion of the hourly solar irradiation (kWh/m^2) and the inverter efficiency (%). The equation in [162] guided the calculations. See Appendix Six for a full listing of operations design assumptions and considerations.

6.3.2.1.1. Solar-PV system cost consideration

A 20 year operational lifetime was considered when determining system cost prices. The PV panels' costs were based on wholesale prices [74]. The other costs taken into account for the PV system include the land costs, balance of system (BOS) costs (excluding battery storage costs) and PV panel maintenance costs. Maintenance costs (cleaning schedules) were considered due to the location of Olowos Plaza and its susceptibility to seasonal dust accumulation [75]. Equation (1) was used in determining the lifetime (Lt) costs for the solar-PV systems' capacities. See Appendix Seven for a full listing of the systems' cost assumptions and considerations.

$$Total\ Cost = Cost\ (capital) + Cost\ (maintenance) + Cost\ (replacement) + Cost\ (land) \qquad (1)$$

6.3.2.2. Battery storage system

Flooded, deep-cycle, lead-acid batteries (the industry workhorse) were selected as the technology for the battery storage system. "Rolls" batteries were selected due to capacity and cost considerations. We employed brute-force search in determining the battery capacity for our system array. The search compared 6 V and 12 V battery types from three battery manufacturers (others being "Trojan" and "Crown" batteries) against possible application "C-rates" (10 hr, 13 hr and 15 hr) and depth of discharge (10%, 20%, 30% and 40%). We opted for a "48 V" system and limited an array to three parallel connections, with reference to the "Rolls" battery manual [76]. Also referencing the manual [76], we employed a multi-stage (bulk, absorption and float) battery charge for the "charging" phase in the battery array's operation cycle. See Appendix Six for further details on the battery storage system's operation design.

6.3.2.2.1. Battery storage system cost consideration

The capital, replacement and maintenance costs for a 20 year operational lifetime were considered for the battery storage systems. Equation (2) was employed in realising the lifetime costs for the different battery storage capacities. See Appendix Seven for further details on battery storage system costs.

$$Total\ Cost = Cost\ (capital) + Cost\ (maintenance) + Cost\ (replacement) \qquad (2)$$

6.3.2.3. Generator system

The fossil fuelled generator system consists of one “19.3 kVA/15.5 kW” diesel-fuelled and one “2.8 kVA/2.2 kW” petrol-fueled generator installed at the canopy level operating in prime power mode. 3-phase, direct-injection generators with a rotation speed of 1500 rpm were considered for the system. Pertaining to system lifetime, we were guided by “HOMER” – a software on distributed generation power system design and optimization [77], whilst considering the system’s mode of operations. See Appendix Five for further details on the generator system’s operation design.

6.3.2.3.1. Generator system cost consideration

The capital, replacement, fuel and maintenance costs for a 20 year operational lifetime were considered for the generator system. Equation (3) was used in determining the generator system’s lifetime costs. See Appendix Six for further details on these costs.

$$Total\ Cost = Cost\ (capital) + Cost\ (maintenance) + Cost\ (replacement) + Cost\ (fuel) \qquad (3)$$

A life cycle cost analysis (LCCA) was carried out on the different IPS for their operational lifetime. The real discount rate was calculated considering inflation at 11.4% and nominal interest rate at 14% [78, 79].
For the calculations, we employed the equation:

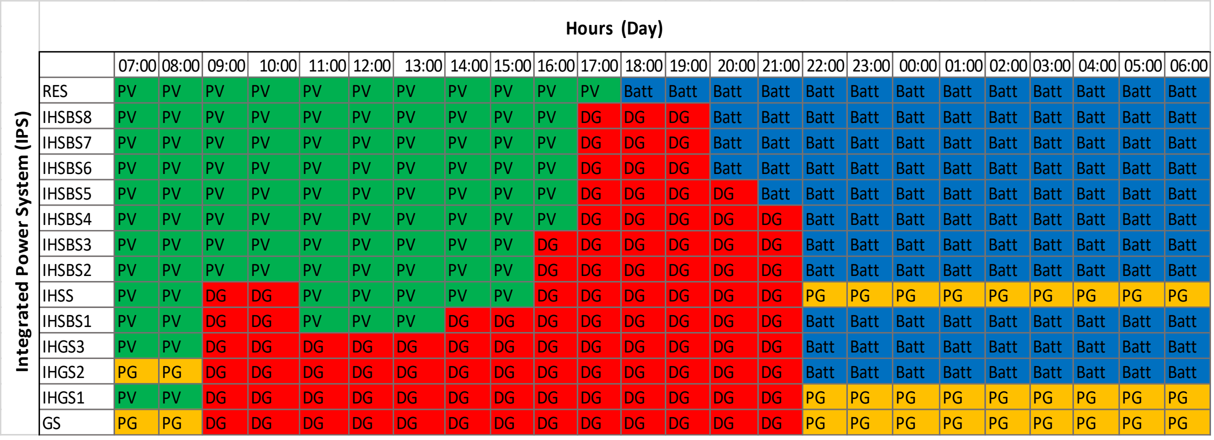
$$\mathrm{r} = (\frac{1+i}{1+n}) - 1 \qquad (4)$$

where:
r = real discount/interest rate;
i = nominal interest rate; and
n = inflation rate, taken as 2% representative.

This rate was used in calculating the present value of the maintenance, operations and replacement costs for the lifetime of the 14 IPS analysed. Diesel and petrol costs [80, 81] were considered for the generator system. The solar-PV system cost accounts for the BOS components costs, as well as the charge controllers and inverter capital and replacement costs. Appendix Seven details the LCCA on the IPSs.

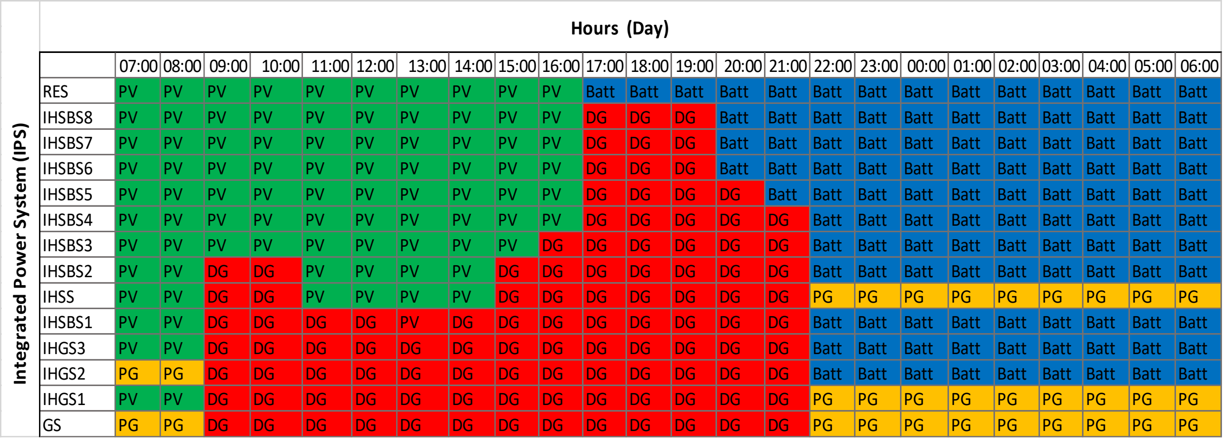
6.3.3. System operations of the different IPS

Figures 6.6, 6.7 and 6.8 indicate the hourly system operations of the different IPS for a typical weekday, Saturday and Sunday respectively. In these representations, the following codes are used to indicate the main power source for each hour of the day: Photovoltaic – PV; Battery – Batt; Diesel Generator – DG and Petrol Generator – PG.



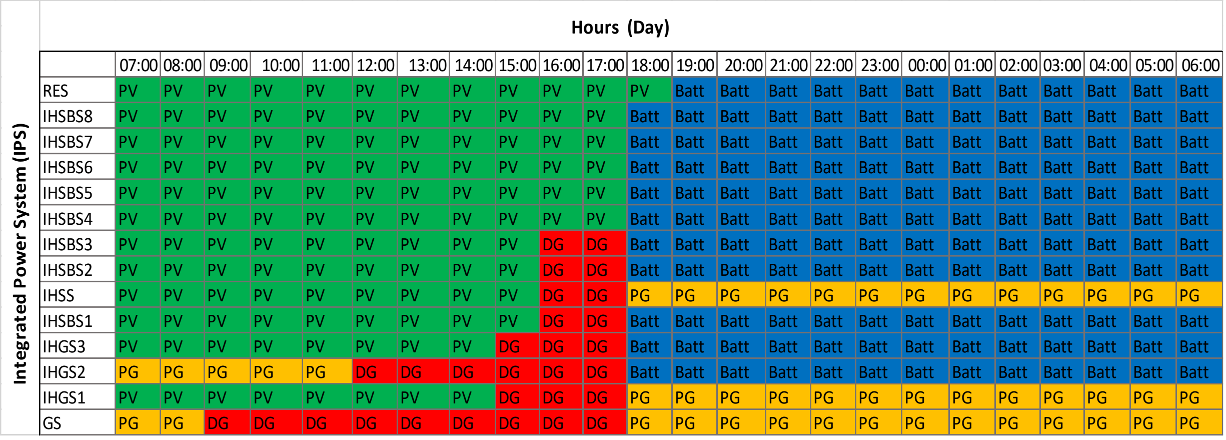
Integrated Power System (IPS)	Hours (Day)																							
	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00	02:00	03:00	04:00	05:00	06:00
RES	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS8	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS7	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS6	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS5	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS4	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS3	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS2	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSS	PV	PV	DG	DG	PV	PV	PV	PV	PV	DG	DG	DG	DG	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG
IHSBS1	PV	PV	DG	DG	PV	PV	PV	DG	DG	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS3	PV	PV	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS2	PG	PG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS1	PV	PV	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG
GS	PG	PG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG

Figure 6.6 – Hourly system operations of the different IPS for a typical weekday



Integrated Power System (IPS)	Hours (Day)																							
	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00	02:00	03:00	04:00	05:00	06:00
RES	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS8	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS7	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS6	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS5	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS4	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS3	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS2	PV	PV	DG	DG	PV	PV	PV	PV	DG	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSS	PV	PV	DG	DG	PV	PV	PV	PV	DG	DG	DG	DG	DG	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG
IHSBS1	PV	PV	DG	DG	DG	DG	PV	DG	DG	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS3	PV	PV	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS2	PG	PG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS1	PV	PV	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG
GS	PG	PG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG

Figure 6.7 – Hourly system operations of the different IPS for a typical Saturday



Integrated Power System (IPS)	Hours (Day)																							
	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00	02:00	03:00	04:00	05:00	06:00
RES	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS8	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS7	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS6	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS5	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS4	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS3	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS2	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSS	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG
IHSBS1	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS3	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS2	PG	PG	PG	PG	PG	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS1	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG
GS	PG	PG	DG	DG	DG	DG	DG	DG	DG	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG

Figure 6.8 – Hourly system operations of the different IPS for a typical Sunday

6.3.3.1. Rationale for the IPS' operations design, planning and management

The PV and DG (of the Generator system (GS)) met the larger loads (10.8 kWh, 9.2 kWh and 7.5 kWh) during the day. The PG of the GS, met the lesser loads (0.42 kWh) throughout the night. The DG was preferred (more energy per litre consumption and better power conversion efficiency) over the PG in meeting the larger loads alongside the PV during the day. The excess generation from the PV system during the day, charged the batteries. In the systems where there was no GS, the battery storage system serviced the lesser loads throughout the night. In this study's operations design, the GS did not charge the batteries. The battery storage system's charge was provided by the PV system. The multi-stage battery charging regime i.e. approximately two hours to get to 80% state of charge (SOC), six hours to 100% SOC, was considered. For efficiency, the DG operated for at least two hours whenever deployed. Diesel fuel produced 10.8 kWh/L and gasoline (petrol) 9.7 kWh/L [163]. This knowledge, product specification (litres required for a full tank) and the power conversion efficiency of the GS determined the frequency of fuel procurement. It also informed operations design and energy management considerations. Diesel fuel was considered to produce 2.68 $kgCO_2$ per litre consumption and petrol – 2.31 $kgCO_2$ per litre consumption [39]. This enabled the calculation of emissions (CO_2 tonne/yr.) based on frequency of usage (how often?) and the intensity of use (how much per usage?). See Appendix Six for further details on assumptions and operations considerations. In comparison to a pure GS, the hybrid configuration afforded the commercial centre savings on cost i.e. fuel usage, as well as, extending equipment service life. By deploying the most efficient power system in meeting load demand at different times (hours) of the day, there was also the opportunity for emissions reduction. This is based on systems configuration and how the three (power) systems were integrated for operations. In designing the power systems' operations to meet specific load demand in the commercial centre, efforts were made towards energy efficiency and energy saving. The performance of the power system solutions are contingent on the commercial centre's operations i.e. each outlet in the commercial centre is limited to a number of energy consuming devices/equipment. In scaling the commercial centre's operations, power systems can be implemented for simultaneous (duplicity of) operations i.e. batteries being charged by generators as well as PV system. At the end of the day, energy management and overall system performance, boils down to what the system is prioritised (energy saving, cost saving, emissions reduction etc.) for.

6.4. Results

From our analysis, the "IHSS" is the cheapest ($162,225) IPS of the 14 power systems analysed. Olowos Plaza will make power system cost (capital, replacement, operations and maintenance) savings of up to 55% when compared to the average power system costs ($358,578) for its operational lifetime. The plaza will make further power system cost savings of up to 26% when compared to the "RES" – the most costly ($867,436) power system for the analysis. Figure 6.9 represents the various IPS' costs

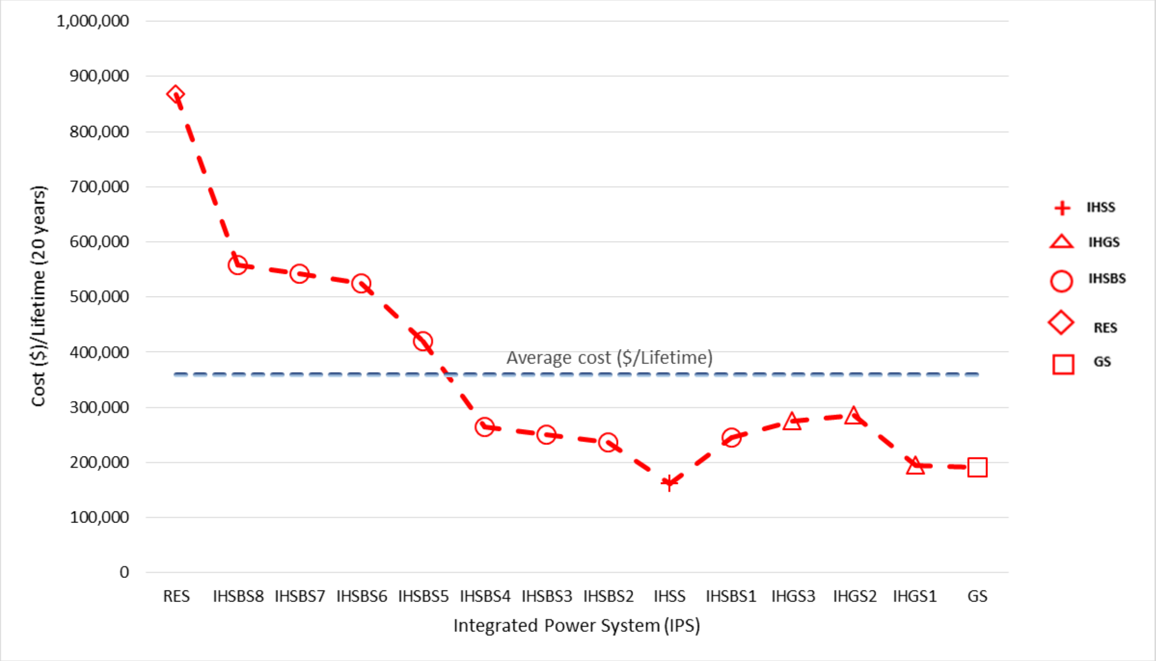


Figure 6.9 – Total lifetime cost of all IPS, in descending order of percentage renewable contribution

Informed by power distribution companies' (DisCos) unwillingness to transact with embedded generators (with excuses of network maintenance and rehabilitation), and with all but one of the power systems generating surplus energy (MWh/yr.), we factored in the surplus energy performance metric. We hypothesise that the inability to capitalise on the surplus energy generated by Olowos Plaza power systems' operations would be more impactful to the systems at the upper limit of the surplus energy metric, especially with the plaza permitted to operate without a power distribution license in all the power system capacities considered [82]. Figure 6.10 represents the IPS' costs and surplus energy relationship.

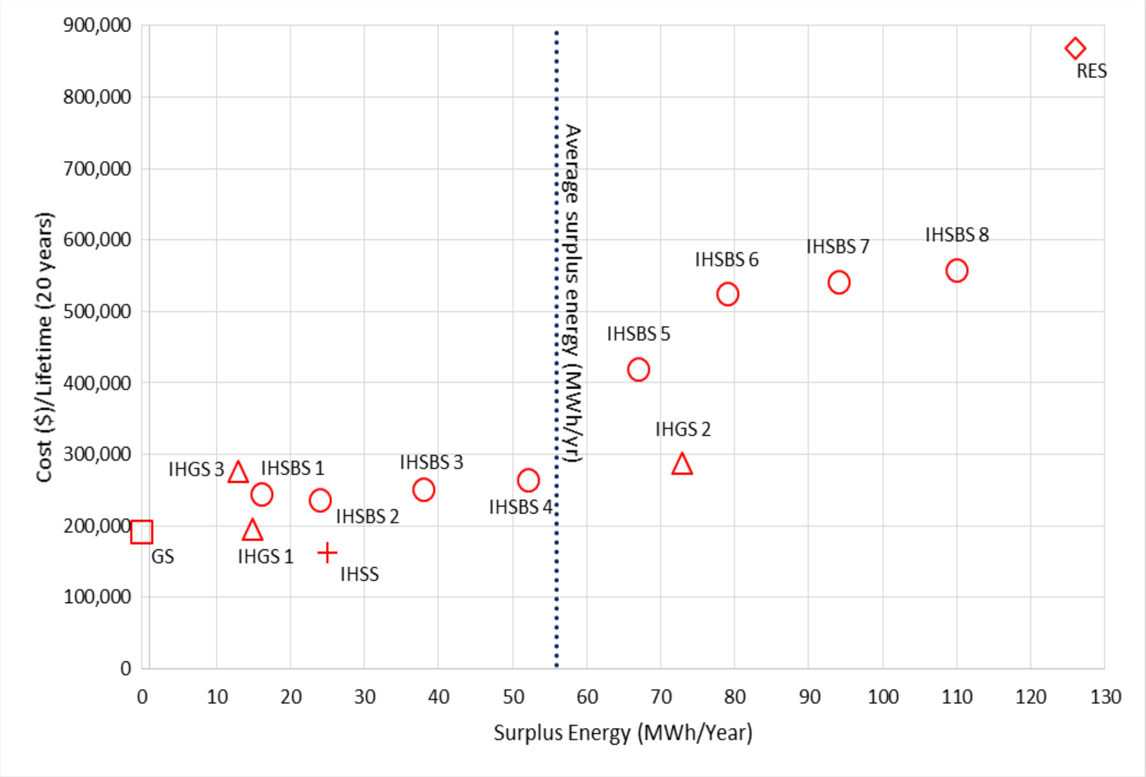


Figure 6.10 – IPS' costs and surplus energy relationship in ascending order of surplus energy generated

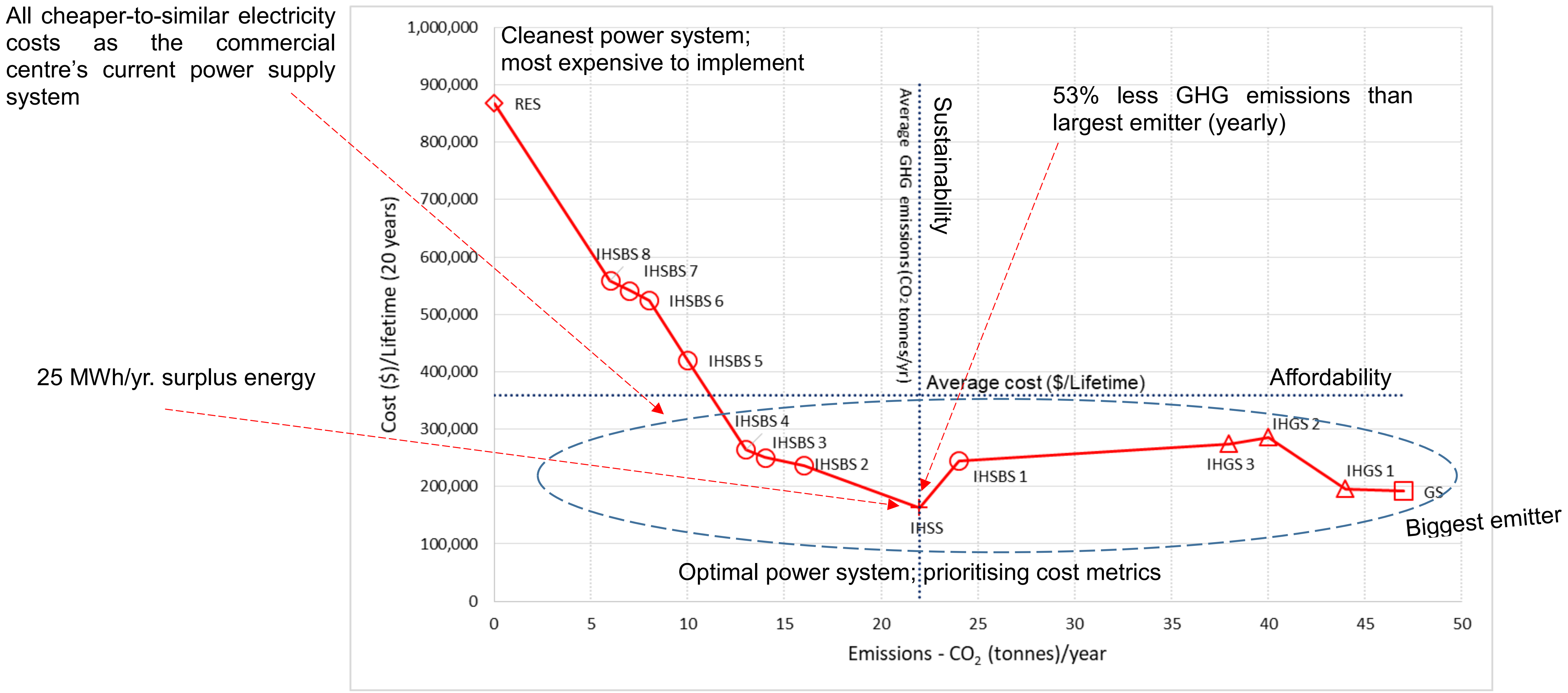
The "GS" is the only power system of the 14 analysed that generated no surplus energy through its operations. As an outlier it was not included in calculations determining the average surplus energy (56 MWh/yr.). The "RES" through its operations, generated the most surplus energy (126 MWh/yr.) of the systems'. With no operational transactive electricity market (TEM) in place, we considered the systems with surplus energy generation above average as non-feasible with precedence set on system operations efficiency i.e. closely matched supply-demand ratio (systems generating below the average surplus energy). In light of these, eight of the fourteen IPS analysed were found to generate surplus energy below the average.

In determining the CO_2 (tonnes/year) value for the different IPS, we worked with diesel fuel emitting 2.68 kg per litre consumption and petrol emitting 2.31 kg per litre consumption [39]. Figure 6.11 (hockey stick graph) represents the IPS' costs and GHG emissions relationship.

6.4.1. Sensitivity analysis of the battery lifetime

The study made reference to "Rolls" battery manual [76] when implementing the battery storage systems' operations design. During the course of the analysis, a relationship was established between DOD and battery lifetime. This was further explored by conducting a sensitivity analysis. The analysis focussed on the "RES" operations design implemented for this study. The analysis explored the system in operation at different DOD (10 – 80%). The "Rolls" battery manual [76], set the 40% DOD number of cycles at 3700. This informed the cycles of the other DOD in the range. The RES implemented for this study operated at 38% (approx. 40%) weighted average DOD for the week and required a single array replacement (excluding initial installation) throughout the lifetime (20 years) of the commercial centre's operations. Its operational capacity was 82 kWh.

When the RES was analysed with a 10% DOD, the battery array replacement exceeded the lifetime of the commercial centre i.e. 40 years. With an installed operational capacity of 328 kWh (a 400% increase in capacity over the default RES), providing 14,800 cycles in service. At 80% DOD, the RES would need an array replacement approximately every five years and three other times during the lifetime considered for the study. At 70, 60 and 50%, array replacements would occur every six, seven and eight years respectively. These results were evaluated to elicit how they could affect the implementation of a hybrid system or fully renewable energy system with regards to cost implications. The battery storage cost (initial installation and replacement) of the RES system implemented for this study, made up 89% of the total lifetime cost of the system (with the PV system factored in). The RES system analysed for 10% DOD operations had a battery storage system (excluding the PV system) capital cost ($1,344,000) that was 55% more than the total lifetime cost ($ 867,000) of the RES (40% DOD) implemented in the wider analysis of this study. These results show that PV systems are cheaper to implement without the added costs of battery storage systems. The IHSS system in Figure 6.11 corroborates this.


All cheaper-to-similar electricity costs as the commercial centre's current power supply system

25 MWh/yr. surplus energy

Cleanest power system; most expensive to implement

53% less GHG emissions than largest emitter (yearly)

Optimal power system; prioritising cost metrics

Biggest emitter

Figure 6.11 – IPS' costs and GHG emissions relationship in descending order of percentage renewable contribution – Adapted [100]

The “RES” is the only power system of the 14 analysed that emitted no greenhouse gas through its operations. As an outlier it was not included in calculations determining the average GHG emissions (22 CO_2 tonnes/year). The “GS” through its operations, generated the most GHG emissions (47 CO_2 tonnes/year) of the systems. Furthermore, and with emphasis on GHG emissions, the following power systems were feasible: IHSS, IHSBS 2, IHSBS 3, IHSBS 4, IHSBS 5, IHSBS 6, IHSBS 7, IHSBS 8 and RES. The following were also feasible when assessing the systems for cost implication: GS, IHGS 1, IHGS 2, IHGS 3, IHSS, IHSBS 1, IHSBS 2, IHSBS 3 and IHSBS 4, with a review on the systems’ surplus energy returning these: GS, IHGS 1, IHGS 3, IHSS, IHSBS 1, IHSBS 2, IHSBS 3 and IHSBS 4, as practicable.

Considering all impact/performance metrics, we realised a feasible solutions (“sweet spot”) region for Olowos Plaza. The region comprises hybrid power systems, with one solar-PV based system (IHSS) and three solar-PV and battery based systems (IHSBS 2, IHSBS 3 and IHSBS 4). In light of these, the “IHSS” is the most viable power system solution of the 14 integrated power system operations analysed. It best satisfied the conditions of the impact assessment defined by the three impact metrics of; cost implication ($/lifetime (20 years)), GHG emissions (CO_2 tonnes/yr.) and surplus energy (MWh/yr.) – Figures 6.9, 6.10 and 6.11 respectively. Summarising the result of our analysis, we present the following salient points:

i. The “IHSS” is the cheapest power system option, with surplus energy of 25 MWh/yr., 80% less than the largest surplus energy generator and emitting 53% less GHG emissions than the largest emitter.

ii. With a tariff of $0.12/kWh for commercial (single and 3-phase) customers [83], an average of 35.8 hours of electricity per week [84] and commercial centre residents incurring an extra $0.20 – 0.30/kWh on generators for security of supply [84], the *GS, IHGS 1, IHGS 2, IHGS 3, IHSS, IHSBS 1, IHSBS 2, IHSBS 3 and IHSBS 4* all provide off-grid power solutions that are reliable with cheaper-to-similar costs as the commercial centres’ current power systems. (See Appendix Six for conversion rates.)

iii. The choice of a petrol generator over a battery storage system led to significant lifetime cost savings for the “IHSS” to the sum of $74,446 when compared with the “IHSBS 2”. Although, the “IHSBS 2” performed slightly better than the “IHSS” against the other impact metrics i.e. generated approximately 1 MWh/yr. less surplus energy, emitting 6 tonnes fewer CO_2 emissions.

iv. Focussing on the IHSBS’ and referring to Figure 6.11, we observe a distinct transition from IHSBS 4 – IHSBS 5, an inflection point in our systems analysis with feasibility ramifications. The marginal cost of increasing the renewable percentage contribution begins to increase at the transition from IHSBS 4 – IHSBS 5.

v. Guided by Luckow *et al.’s* [85] report, we introduced a carbon tax ($25) on the generator (GS) and hybrid generator-based systems (IHGS 1, IHGS 2 and IHGS 3) and still found them cost competitive (average increase of $0.03/kWh in levelized cost of energy (LCOE)) when compared to commercial centres’ current power systems.

vi. The design and installation of a generator system at the canopy level for commercial centres allows for easier monitoring of air quality and implementing carbon air filter technologies. It also addresses the proliferation of small-scale petrol generators from shop to shop and floor to floor, improving air quality and mitigating the adverse effect of generator fumes on the health [44, 47, 58].

vii. Renewably-powered commercial centres, vanguard a transition to smart energy systems that ensures commercial centre residents energy consumption and usage are cost-reflective. For Olowos Plaza, this would result in commercial outlet 1 paying 47% of the Plaza’s total yearly electricity costs, outlet 3 – 41%, outlet 5 – 10% and outlets 2 and 4 paying 1% respectively. Refer to Appendix Four for the commercial outlets activities.

6.5. Discussion

Results from our case study analysis demonstrate beneficial electrification for the commercial sector through renewable-centric grid defection solutions. Total grid defection solutions also present an opportunity for the DisCos to increase the duration and improve the quality of electricity supply to the residential sector by reducing the number of energy intensive C&I customers connected to their network. These non-wire alternatives (NWA) could also be explored in partial grid defection configurations by incentivising surplus energy generation through policy mechanisms like net energy metering (NEM). It would mean electricity is made available during periods of peak demand and in emergencies.

In bolstering economic development, surplus energy generation could yet be pivotal in propelling the formation of a transactive electricity market (TEM) through C&I coalition formations that could further develop into hubs, clusters and villages. Reiterating recommendations by [66], further deregulation of the electricity sector to accommodate more independent power producers, embedded and captive power generators could be pivotal to increasing urban and rural electrification. As such, TEM would have to be backed by policy and an adequate regulatory infrastructure. The democratization of the electricity sector to involve more non-conventional power producers by introducing different pathways (generation to consumers) as opposed to the traditional power delivery structure (generation to transmission to distribution to utilisation) increases business competition (through direct competition or partnerships) with the DisCos that could drive customers electricity supply costs down.

We posit that the C&I sectors transitioning to prosumers generating excess electricity could by extension electrify the residential sectors provided adequate legislative and regulatory frameworks are in place. We refer to this initiative as “Commercial Electrification of the Residential Sector (Comtridential)”. This could be in partnership with the DisCos (requiring further investments in revamping and modifying their electricity infrastructure/networks) or directly with the residential sector focussing on residential estates. The latter would require significant investments in the deployment of power distribution infrastructure. The potential for this energy solution could be measured by the willingness of residential estates (middle to high income earners) in maintaining access to an electricity supply network and increasing the duration of supplied hours. Given the electricity supply situation, an example of customer willingness in remaining electrified draws from the collective efforts of estate residents in funding the replacement of damaged service transformers resulting from power surges due to grid unreliability and intermittency.

The transition to sustainable solutions as a means in electrifying the various sectors that contribute to the socioeconomic development of a nation is possible and is being exemplified in Nigeria through a public sector led initiative. The Nigerian government through its rural electrification agency (REA), in partnership with private investors and multilateral finance institutions (The World Bank and African Development Bank) are deploying solar-PV powered utility-scale (stand-alone) systems in improving electricity supply to the commercial, industrial, education and health sectors [86]. These solutions are being implemented under two initiatives (Energising Economies and Energising Education), underscoring the importance of non-fragmented finance by international donor organisations and multilateral institutions as elicited by [62].

6.6. Limitations of the study

There is only so much that can be accounted when implementing a systematic quantitative analysis, that is already pre-defined in an energy modelling/ software environment. Also, the scale of hybrid systems operations design (in terms of numbers) as well as, system testing iterations were limited. The approach to the analysis was mainly determined by the researcher i.e. the cost and environmental implication of deploying the GS in charging the batteries could have been studied. Other factors (ambient temperature, system location and the effect of derating on battery efficiency) that affect battery storage systems lifetime were not analysed in more detail.

6.7. Conclusions

The results of this analysis show that a practical approach of adopting hybrid systems with PV, batteries and fossil fuel generation in urban commercial settings in Nigeria will greatly reduce lifetime energy costs and deliver reliable power to loads while simultaneously contributing to decarbonisation and improving air quality by reducing overall reliance on fossil fuel self-generation. It also elicited the non-essentiality of energy storage systems (high cost considerations) in regions of abundant solar energy resource especially for hybrid energy systems that also incorporate non-renewable sources of power generation. The IHSS evidenced this, by best satisfying the economic and environmental metrics of our analysis i.e. being the cheapest power system option and emitting 53% less GHG emissions than the largest emitter. Also, from this study, we realised that disparate energy solutions would have to be explored in meeting country-level and regional electrification targets in the medium to long term. Our case study results further highlighted total to partial sustainable grid defection solutions as practicable solutions for urban electrification, with a unique case presented for the commercial electrification of the residential sector (Comtridential) through commercial and industrial coalition formations taking advantage of the generation of surplus energy from hybrid renewable energy systems operating in a liberated transactive electricity market.

Our case study on commercial centres informed the reality that most project developers assess their project feasibility solely on its cost implication, disregarding its social and environmental effects. Therefore without adequate climate policies, the generator and three generator-based hybrid systems (GS, IHGS1, IHGS2 and IHGS3) emitting 47, 44, 40 and 38 CO_2 tonnes/year respectively, would have been considered feasible. Focussing on the issue of climate change, sustainable energy solutions are being favoured in electrifying rural SSA. The deployment of sustainable energy solutions addresses the regional electrification crisis in tandem with mitigating the effect of climate change. Energy policy formulation that serves as a proper deterrent to carbon-intensive processes of the commercial, industrial and power sectors present a more impactful approach in reducing carbon emissions and mitigating the effect of climate change beyond small-scale, renewable-centric, grid defection solutions. Consequently, the role of individual nation’s government in improving regional electrification rates, both in urban and rural areas, cannot be overemphasized. Government support through policy actions and ensuring an enabling regulatory environment are essential in driving the energy transition through the implementation of sustainable energy solutions. These precursors form the bedrock to improving access to finance, implementing policy mechanisms, dissemination of information & technology, initiating sectoral reforms and community engagement. Ready access to reliable data across the region is also important in informing financial investments and implementing sustainable development projects.

In light of these, if the United Nations SDGs are to be met by 2030, it is important that SSA's rural electrification agenda goes beyond lighting and provides the required energy that could stimulate socioeconomic activities towards the collective development of communities, broader countries and the wider region. Sustainable electrification targeting core urban sectors (commercial, industrial and residential), are channelled measures in addressing the attendant consequences of urbanisation and spurring economic development through industrialization. Therefore, it is critical that rural electrification is sustained alongside efforts of extending electrification, improving the quality of power delivered and increasing the duration of electricity supply access to urban areas.

CHAPTER SEVEN

The transition to an energy autonomous multi-sector

Preamble

The Nigerian federal government is taking steps towards improving, increasing and extending electrification to served, underserved and unserved communities respectively. The countrywide electrification efforts are being implemented by the government through initiatives and programmes under the auspices of significant stakeholders (TCN and REA) in its energy sector [106 – 107]. Initiatives earlier discussed such as; the ERGP, PSRP, NEP, EEI, EEP and TREP are strategic efforts by the government in addressing the widening supply-demand gap.

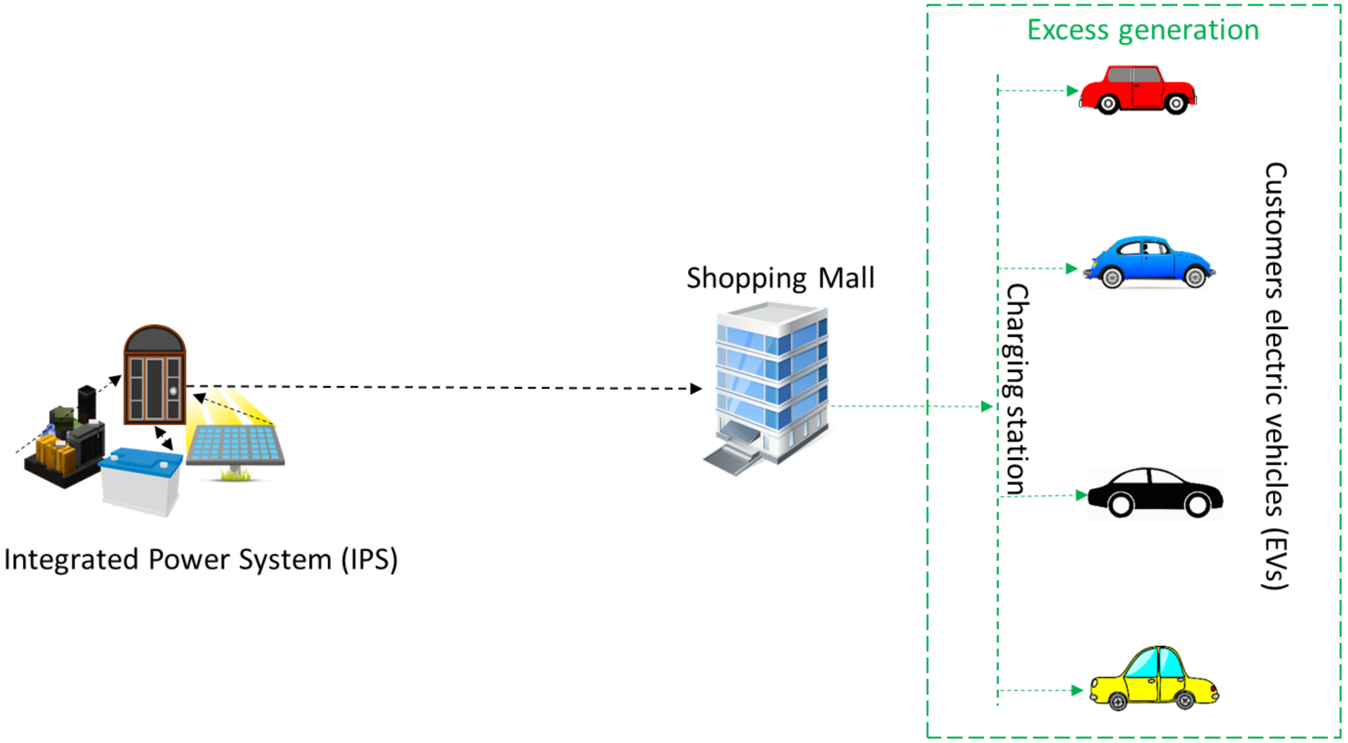
These financial and technical interventions are intended to enhance the performance of the nation’s electricity supply value chain (Generation – Utilisation). The federal government’s electrification drive is also supported by the private sector, international finance institutions, international development agencies and organisations [108 – 109].

In light of these, it is important to note that the Nigerian government has recorded a level of success in its electrification agenda through the REA under the EEI and EEP initiatives [107]. The commissioning of an off-grid power solution for Sura shopping complex (commercial centre) [110] and the ongoing off-grid power development project for the University of Lagos (UniLag) [111] are notable projects that evidence this.

Nonetheless, an ever growing population, increasing need for energy and digitalisation present an uphill task in realising the government’s electrification agenda for the long term. The lack of a countrywide maintenance culture [112], particularly affecting government owned and operated critical infrastructure and assets, has led to a deterioration of public facilities such as; refineries, power supply infrastructure, hospitals and academic institutions with ramifications on the broader country [112].

The transition of critical sectors from energy dependent to energy autonomous sectors would augment current governmental efforts in improving, increasing and extending electrification. Energy autonomy present pathways for extending electrification to the multi-sector through grid defection and multi-sectoral collaborative efforts. It also enables businesses to optimise the implementation of their power systems, thereby improving productivity and quality of life. Power system maintenance (preventing a decline in system performance over their lifetime) is better achieved by deploying decentralised power solutions defined by maintenance schedules [100]. This thesis posits that the government's electrification agenda might still result in power supply deficits owing to the extent of the supply-demand gap (continues to widen) and an elusive maintenance culture. Decentralising power system solutions for the multi-sectors and facilitating an electricity market structure that thrives on collaboration and/or competition of independent prosumers and DisCos are essential elements that would further leverage on Nigeria's unbundled power sector. Figures 7.1 and 7.2 illustrate how Nigeria's private sector can collaborate or compete against DisCos in electrifying the country.

Corporate and social responsibility (CSR) of the commercial sector: Large scale commercial centres like shopping malls secure tax abatements/holidays from the government by dedicating a section of their parking lot for the seamless charging of EVs at a subsidised price



**Developing an EV charging station within the commercial complex, incentivises the transition to sustainable transportation*

**Sustainable energy systems = Sustainable commercial centres and transportation*

**Thereby, establishing a link between the power, commercial and transportation sector*

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Figure 7.1 – Creating a sustainable environment through corporate and social responsibility

Driving sustainable electrification and creating a sustainable environment through industrial end-to-end solutions i.e. secure electricity supply at work, reduced GHG emissions, secure housing for workers with 24 hrs power supply, low cost of fuel for workers with EVs, taking advantage of TEM and partnering with DisCos (reverse In-DisCos) in increasing electrification to other sectors i.e. public, education, health etc.

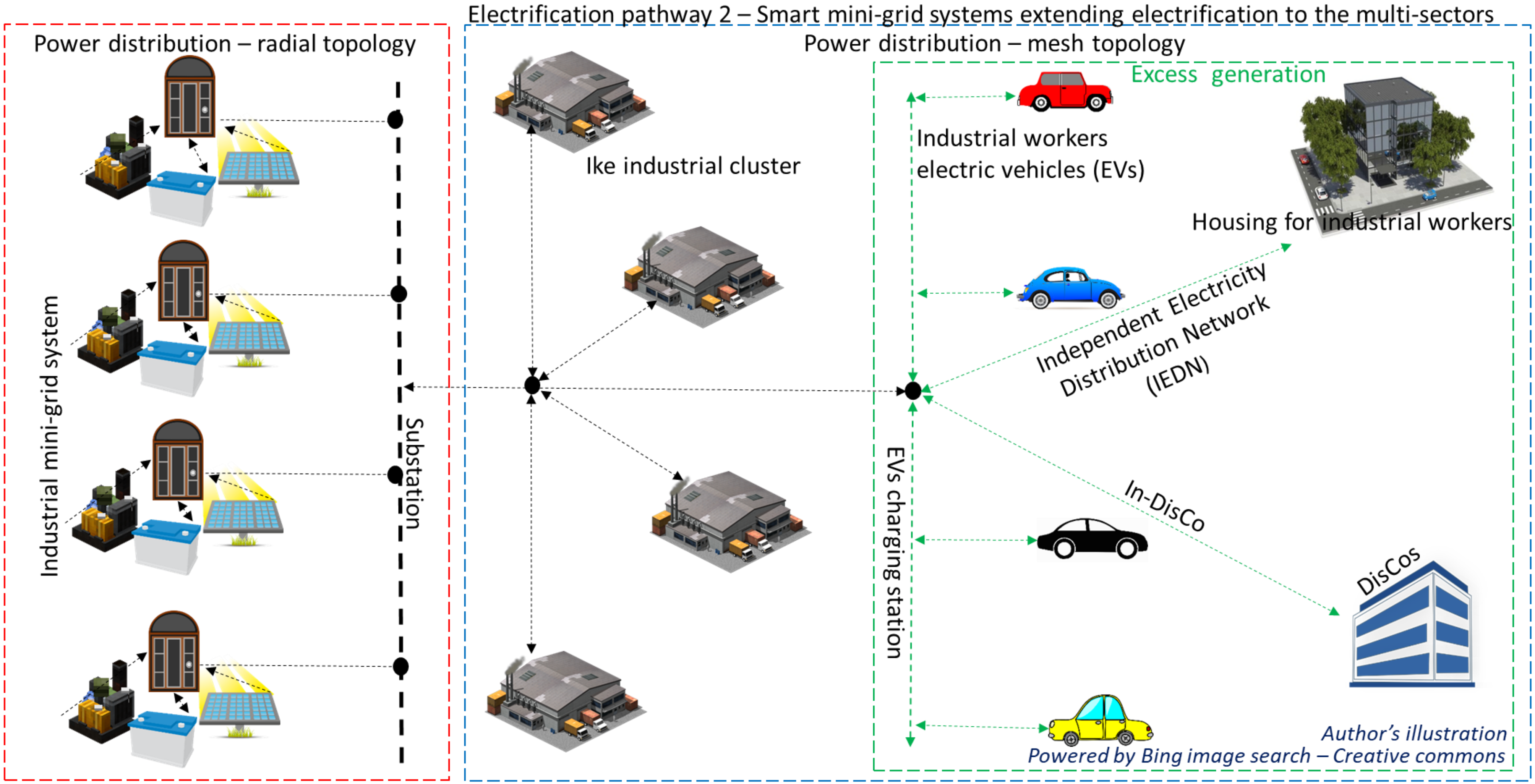

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Figure 7.2 – Industrial pathway to increasing countrywide electrification

A significant portion of this chapter is from the paper – Optimising photovoltaic-centric hybrid power systems for energy autonomy. Energy Reports. 7, pp. 1943 – 1953. https://doi.org/10.1016/j.egyr.2021.03.039

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Abstract

In recent years, emphasis has been placed on the design and implementation of sustainable energy system solutions to combat the adverse environmental impact of emissions from the power and transportation sectors. This study applies a systems elimination method using numerical simulation to validate and optimise recently-reported results demonstrating the benefits of photovoltaic (PV) – diesel – battery hybrid integrated power systems (IPS) for commercial centres, with Abuja in Nigeria used for the case study. An optimal IPS was identified from 20,200 candidate solutions analysed by assessment against environmental (1st priority) and economic (2nd priority) metrics. Although environmental conditions were prioritised, the optimal system was economically viable. The environmentally optimal system emitted 33% less greenhouse gas (GHG) emissions (CO2 tonnes/yr.) than the economically optimised solution (PV–diesel) over their operational lifetimes ($/20 years), and was 4% costlier than same. The results demonstrate that carbon taxation or outright bans on independent fossil fuel systems (IFFSs) in emerging economies might not be effective policies in mitigating the impact of climate change on our environment. This study contributes to the body of knowledge on energising unserved and underserved communities in sub-Saharan Africa, considering the case study country of Nigeria. It decries the common practice of prioritising economic factors over environmental factors in optimising the operations of grid defected power system solutions as continental and regional electrification efforts are being ramped up. This is particularly of importance (a social responsibility), as immediate economic gains could have far-reaching environmental and social implications that elicits the limitations of economically prioritised power development projects in the offing.

Keywords: environmental assessment; economic assessment; hybrid renewable energy systems; PV autonomous systems; sustainable electrification; climate change mitigation

7.1. Introduction

In attaining global electrification, human efforts must be multidimensional; in other words, ensuring access to affordable, reliable, sustainable and modern energy for all is central to the realisation of the United Nations' sustainable development goals (SDGs) [40]. As such, it is imperative that a synergy of both renewable and other power sources [140] is implemented for the multiple sectors that contribute substantially to the economy. Also integral to the electrification agenda are enablers in the form of financial support from public/private institutions and consolidated governmental and inter-governmental policy actions [90].

The electrification drive adopts different forms at both ends of the economic development spectrum. The developed world is investing human, technical and financial resources in studying and re-engineering the power systems that service their sectors (with notable interest in the transportation sector) [141]. They are becoming more energy, process and resource efficient – as countries drive their transition to sustainable solutions [90, 16]. At the other end, the developing world (low – middle income countries) still grapples with the reliability and resiliency of their power grid systems and securing electricity supply access for the unserved and underserved communities [41, 95]. This situation has led to the continued investment in conventional power systems (coal power generation) in countries like South-Africa, Malawi and Zimbabwe, for example [42], thus posing a challenge to the energy transition.

The paucity of power supply in emerging economies which requires focus on poverty reduction, food security, economic growth and development, presents an opportunity in implementing sustainable energy solutions towards addressing the power supply deficit. This is exacerbated by deficient electricity infrastructure, struggling to keep pace with a growing population [42]. As these countries industrialise towards stimulating their economic activities, greenhouse gas (GHG) emissions will inevitably rise [92] if the primary sectors (commercial and industrial (C&I)) spurring industrialisation and urbanisation remain heavily dependent on unreliable conventional grid power systems. It becomes an environmental and health issue when the deficiency of the centralised power grid is ameliorated by cost-prohibitive [1, 94] and unsustainable independent fossil fuel solutions (e.g. petrol and diesel generators).

The tendency to analyse the economic viability of power systems development projects in isolation or as a priority over socio-environmental factors, has long term implications on the environment and people's social wellbeing. GHG emissions and fumes from independent fossil fuel systems (IFFS) would ineluctably contribute to climate change with adverse effects on the environment [90] and human health conditions [47]. Adopting a reactive culture in addressing the problems that could arise from implementing conventional power systems (coal power generation) and/or IFFS in bridging the power supply deficit in emerging economies, could prove costlier in the long term than rolling out renewable energy system (RES) or hybrid renewable energy system (HRES) solutions. Considering the equal importance of socio-environmental factors with economic factors in optimising HRESs design [139] is a more impactful approach towards realising holistic power system solutions for emerging economies.

Therefore implementing third generation HRESs that includes solar-photovoltaic (PV) generation and diesel generators, could drive the transition to sustainable energy system solutions for the developing world. The HRES's operations could be supported by interactive devices (e.g. remote monitoring systems and energy consumption meters) [93], and optimised to satisfy economic, environmental and social metrics. These could be more effective than carbon taxation (based on the current pricing structure) [85] and outright bans on IFFS in access-deficient regions.

7.2 Review of relevant studies

The review of literature was undertaken to highlight the emphasis placed on economic over environmental factors in power systems design and operations analysis. Where economic metrics continue to be prioritised, social actions/responsibilities could be key in tipping the scale and advancing the transition towards a sustainable environment.

7.2.1. The viability of grid defected power system solutions

Studies have found that grid defected integrated power system (IPS) solutions could be more affordable than conventional power grid systems both in the developing [84] and developed [94] world. Supporting these findings, Olowosejeje *et al.* [100] adopted a systematic quantitative analysis in evaluating the techno-economic and environmental viability of grid defected power system solutions for commercial centres in Abuja, Nigeria. The integrated hybrid solar-PV based system (IHSS) in the study, was the most viable power system of the 14 power system solutions analysed. Olówósejéjé *et al*.'s study prioritised economic viability in selecting an optimal power system solution for commercial application. Peffley and Pearce [94] utilised an energy modelling software – Hybrid Optimisation Model for Electric Renewables (HOMER) in analysing the techno-economic viability of hybrid solar-PV systems for the commercial sector (small and medium enterprises) in the Upper Peninsula of Michigan, USA. They concluded that a solar-PV hybrid system (including energy storage and natural gas power generators) is technically and economically viable for all scales of commercial utility customers. Their study also laid emphasis on the techno-economic viability of decentralised solutions. For both studies, environmental benefits were incidental to economic considerations and their benefits.

Across the literature, grid defected IPSs in different power system mixes and configurations have been documented to be viable particularly for remote locations i.e. the rural underserved/unserved and critical sectors. Ali and Jang [96] modelled an optimum hybrid renewable energy system (with solar and wind as the main energy sources) in HOMER considering techno-economic (comparing levelised cost of energy and net present cost) parameters for the remote island of Deokjeok-do, South Korea. Their study also evaluated the economic viability of the supporting energy storage system (ESS) technology (battery against pumped hydro storage). The solar-wind-pumped hydro storage system was more economically viable than the solar-wind-battery storage system based on their results. This study focussed on optimising power system solutions for techno-economic viability. Babatunde *et al.* [98] performed a techno-economic analysis in HOMER to determine the feasibility of implementing a hybrid renewable energy system (HRES) for hypothetical rural healthcare centres in the six geo-political zones of Nigeria. The PV and diesel generator (DG) and battery

HRES was economically feasible for all locations studied with some locations considered more feasible than others. The net present cost (NPC) for the power system solutions considered in their analysis was sensitive to fluctuations in the fuel pump price. Their study realised economically viable power system solutions with environmental benefits. All of these studies identified economically optimal grid defected solutions, but the environmental impact of various solutions was not independently determined i.e. the extent of environmental benefits were limited to economically viable solutions.

Franco *et al.* [99] reviewed energy production and storage technologies based on a multi-criteria and multidisciplinary method defined by the EssentialTech programme. Their goal was to realise the most suitable power system solution for healthcare centres in the global south. They presented the hybrid renewable energy system solution (renewable source plus battery storage and DG) as the optimal power system solution for medium to large scale healthcare facilities, particularly those situated in remote areas. The economic implications of the power system solution were the primary consideration of the study. This begs the question, to what extent are the environmental impact of a power system solution truly considered?

7.2.2. The factors considered when designing grid defected power system solutions

When deploying renewable energy (RE) and HRES solutions, energy storage systems (ESSs) usually contribute significant costs to the total power system costs. The sub-optimisation of ESSs could impact the economic viability of grid defected IPS solutions. The choice of integrating an ESS for energy autonomy in advanced economies is usually considered unviable solely on its economic implications. This is especially the case when a reliable and affordable grid connection is available. Grid defection could yet offer environmentally cleaner power system solutions with economic viability if ESSs are optimised and integrated for longer lifetimes. Optimising the ESS component of the power system solution, taking into consideration the choice of storage technology, capacity sizing and the operation strategies implemented could realise environmentally cleaner IPS with economic viability.

An aggregation of autonomous power systems could contribute to decarbonising the environment especially as base load power plants that offer energy access to grid connected energy consumers are usually gas or coal powered. Veilleux *et al.* [97] applied HOMER in remodelling the current rural micro-grid (integrating more PV modules and replacing lead-acid batteries with lithium ion batteries) solution implemented for the case study island of Koh Jik in Thailand. In assessing the techno-economic viability of their remodelled solution, they presented an economic argument for lithium ion ESSs over lead-acid alternatives. Although lithium ion ESS are more expensive than lead-acid ESS, the capacity of lead-acid batteries required to attain the same RE fraction that the lithium ion ESS provided in the off-grid system, drove the total cost of the lead-acid ESS to almost cost parity with the lithium ion ESS. The power system modelling exposed an environmental lapse in their initial power system design and implementation that had economic implications over the long-term. This reinforces the point that optimising the ESS configuration in IPS design could present environmentally viable power systems with economic benefits over the long-term. Foles *et al.* [101] employed Matlab in evaluating the techno-economic viability of solar-PV and solar-PV plus energy storage systems for the residential sector in three representative Portuguese locations. They considered four power system configuration scenarios (solar-PV, solar-PV + grid connection, solar-PV + battery storage and solar-PV + battery storage + grid connection). The locations considered were characterised by differing solar resource potential. Their results elicited the unviability of the scenarios with energy storage systems for residential applications. Their study did not highlight the fact that the prioritisation of economic factors in the choice of power system solutions has an impact on the environmental benefits that a grid defected solution with ESSs could offer.

Cucchiella *et al.* [102] applied a discounted cash flow (DCF) method in analysing the practicality of solar-PV plus lead-acid ESSs in four case study scenarios for the residential sector in Italy. Their conclusions infer that solar-PV plus ESSs is practical when the share of self-consumption is increased through the installation of solar-PV plants in regions with high levels of solar insolation. Although they present a condition for the practicality of solar-PV plus ESSs, their study does not advance the environmental importance of integrating optimised ESSs. Förstl *et al.* [142] applied SimSES – simulation of stationary energy storage systems, an open source software tool in evaluating the techno-economic feasibility of residential solar-PV and battery storage systems. The study presented two case studies with one focussing on the profitability and lifetime of battery storage systems under different energy management and tariff regimes in New South Wales, Australia and Germany. The other placed emphasis on the profitability and degradation impact of three different operation strategies for the residential sector in Australia. Results from case study one highlighted the unprofitability of solar-PV and battery storage systems in both regions with case study two highlighting the beneficial impact of operation strategies on the economic feasibility of solar-PV and battery storage systems. This was at the cost of increased battery degradation. Their study's principal focus considering both case studies, was in optimising the lifetime and performance of the integrated ESS for economic viability. Environmental benefit was not prioritised.

Considering economic factors as a priority over environmental and social factors could have long term economic implications that are not apparent when the immediate economic case is prioritised. This is the case especially when optimising grid defected IPSs design and operations. In an attempt to highlight the neglect of social parameters (job creation and social acceptance) which constitutes an important factor in the implementation of HRESs for small communities, Cuesta *et al.* [143] performed a methodological review of studies that had applied energy modelling software (HOMER, RETScreen, DER-CAM, iHOGA, EnergyPRO) in optimising the design of HRESs. They concluded that except for the latest version of iHOGA, these commercial or open source software had not incorporated social parameters in their models. Their review did not draw the link between social and environmental factors i.e. how GHG emissions can have an adverse effect on the environment and in turn impact jobs in the agricultural sector over the long-term, of how environmental pollution can impact an individual's health and/or quality of life. Babatunde *et al.* [144] followed a multi-criteria (technical, economic, environmental, social and policy) decision making approach in selecting the most suitable HRES for a typical low-income household in Lagos, Nigeria. Their analysis in HOMER was based on two energy demand scenarios – consumer demand with energy efficient devices and consumer demand without. They found the PV-Gen-Battery system to be the most suitable HRES for low-income households when implemented in the energy efficient devices scenario. Although their study considered multiple factors in selecting a power system solution, the economic viability of the power system solution was prioritised over the other factors considered i.e. socio-environmental benefits accompanied the most economically viable solution.

In some emerging economies, governmental policy actions still present a gap in increasing electrification and spurring a rise in economic activities. The paucity of power supply and the limitation of the grid infrastructure in access-deficient regions positions the developing world at the fore in realising sustainable electrification and creating a sustainable environment. Considering metrics of levelised cost of energy (LCOE) and NPC, Agyekum and Nutakor [145] applied HOMER in assessing the economic viability of two hybrid renewable energy systems (PV-Wind-DG-Battery and Wind-DG-Battery) for the commercial sector in southern Ghana. They concluded that governmental effort was imperative in creating an enabling environment that would ensure the economic viability of HRES for sustainable development. Their study did not particularly emphasise the environmental benefits of these systems in application. Emodi *et al.* [146] employed the energy policy modelling and climate change mitigation assessment tool – Long-Range Energy Alternatives Planning (LEAP) in exploring the most sustainable electrification pathway in meeting Nigeria's future energy demand based on four study scenarios. They carried out an energy system analysis and cost-benefit analysis in evaluating the practicality of the scenarios presented. Their results elicited the importance of policy formulation in driving Nigeria's energy transition. It is important that the economic viability of environmentally optimised sustainable energy solutions are clearly presented to adequately inform climate policies.

Rasheed *et al.* [147] argued the case for RE solutions in addressing Pakistan's energy crisis. They supported their argument by carrying out a cross-country comparative study (Pakistan vs rest of South Asia). Their conclusions highlighted effective policy implementation and institutional cooperation as requirements in harnessing Pakistan's renewable energy potential. Their study highlights feed-in-tariff schemes that are already operational in advanced economies as a policy mechanism in driving RE solutions. For emerging markets, this policy instrument might not be effectual due to the underdevelopment of the electricity market. Energy policies that incentivise the proliferation of environmentally optimised HRESs could be more effectual in decarbonising the energy sector, driving sustainable development and developing the electricity market. Ensuring access to affordable, reliable, sustainable and modern energy for all is central to the realisation of the United Nations' SDGs. Adenle [148] carried out a meta-analysis of the literature on the performance of solar energy technologies in three African countries (Ghana, Kenya and South Africa) to explore the role of solar energy in realising the SDGs by 2030. The author concluded that appropriate policy instruments such as; feed-in-tariff schemes, incentive programs and renewable energy laws would drive the uptake of solar energy in African energy markets, thereby contributing to the achievement of the SDGs by 2030. Opposing the author's view and proposing a paradigm shift from a top-down to bottom-up approach in sub-Saharan Africa's electrification agenda could yet present a solution to improving its electrification rate. The uptake of environmentally focused HRESs in this region's critical and economic sectors could be more impactful in realising the SDGs by 2030. The approach of deploying these energy solutions in the critical and economic sectors would simultaneously decarbonise the environment and improve electrification. This strategy could better inform energy (and specifically climate) policies by evidencing the impact of these systems in operation.

7.2.3. How the choice of power system solutions explicates the difference between the energy landscape of advanced economies and emerging economies

The energy landscape of the developed world differs from the developing world. As such, models in increasing electrification cannot be directly replicated. Studies that analyse grid defected IPS solutions primarily for the residential sector in the developed world provide evidence that electricity consumers still favour grid-connected power systems over grid defected IPSs. Their preference is based on power supply reliability and cost implications. Liu *et al.* [149] applied mixed-integer linear programming in determining the techno-economic (parameters of reliability and LCOE) viability of grid defected (solar-PV + battery storage) power systems over grid-connected power supply for 300 homes in Australia. They presented the grid-connected power supply option as the more reliable and lower cost option. Their study reinforces the discourse that in the developed world where reliable grid connection is available, the cost implication of energy access is the primary and possibly sole concern of the energy consumer. Hittinger and Siddiqui [150] considered 1020 locations in the USA when analysing the economic viability of grid defected power systems (solar-PV and battery storage) using their energy system model (ESM) developed in Matlab. They concluded that grid defected power systems are not economically viable for most locations in the USA with the exception of Hawaii and California where policy mechanisms like net energy metering (NEM) could incentivise their consideration. Even in locations where grid defected power systems can take advantage of policy mechanisms like NEM, mechanisms that reward environmentally cleaner grid defected systems are elusive.

In assessing the effect of electricity tariff structure on an electricity customer's decision to maintain connection or defect from the utility grid, Gorman *et al.* [151] employed linear optimisation in calculating a range of off-grid power system costs (considering customer type, location and minimum reliability). These electricity costings were then compared against unique rate tariff structures for over 2000 utilities in the USA. Results highlight the possibility of grid defection beyond current load defection levels. This is subject to a continual fall in solar-PV and ESS technology costs. It is also contingent on if tariff structures are not favourable to the electricity consumer in the offing i.e. utility companies increasing fixed charges and lowering variable charges. Their study sheds light on the fact that grid defection comes second to grid connection in advanced economies, therefore buttressing the point that in the developed world, the onus is on utility companies to decarbonise the power sector.

Whereas, in the developing world, grid defected power system solutions are considered viable in assuaging the impact of grid power unreliability and unavailability on the rural underserved. In emerging economies, the onus to decarbonise the power sector could yet be on the energy autonomous critical/economic sectors. Murugaperumal *et al.* [95] applied HOMER in the optimum design and techno-economic assessment of a HRES for rural electrification in the remote district of Korkadu, India. Their results evidence that the HRES can be a cost-effective sustainable solution to conventional grid power system solutions. The study highlighted the emphasis placed on economic over environmental metrics. Fodhil *et al.* [152] implemented a particle swarm optimisation (PSO) and ε constraint method in optimising the design of a HRES towards concurrently minimising total system cost, unmet load and CO_2 emissions. The HRES (PV-battery-diesel) rural electrification solution realised for the remote village of Tiberkatine in southern Algeria was able to satisfy the aforementioned optimisation conditions. Furthermore, the study presented the PSO approach as more cost-effective with a larger PV penetration fraction than the power system solution realised using HOMER. Although their results realised a solution that satisfied affordable, reliable and sustainable metrics, environmental benefits were limited to economic conditions.

Oyewo *et al.* [153] applied a linear optimisation tool in projecting a cost optimal power system solution for the West African region. Their analysis (for the period 2015 to 2050) evaluated the viability of the transition to fully RE systems based on six policy scenarios considered for the region studied. Their results present the fully RE system as the least cost and least GHG emitting power system solution for the West African region. The study also highlighted solar-PV as the principal energy resource and technology in driving the transition to a sustainable future. Although their study presents an all-RE system as the most economic and environmentally optimal power system solution in the long-term, economic considerations were still prioritised. There is a case to be argued on the extent to which an economically prioritised power system can be environmentally acceptable. In addition, their results are projections for the long-term and not the near to middle term this study seeks to address.

7.2.4. The knowledge gap

Evaluating the practicality of prioritising techno-environmental factors over techno-economic factors in power system design analysis is a knowledge gap identified in the literature this study intends to address. The particular gap this study seeks to fill is in the prioritisation of emissions reduction over cost savings when implementing power development projects in regions with electricity supply deficit. This is imperative as immediate cost savings on power development projects could have long-term adverse effects of an environmental and social bearing. The long-term costs that would be required to ameliorate social (job loss from climate change and adverse health conditions from polluted air) and environmental (mitigating climate change) impact resulting from prioritising cost implications from power development projects, could be significant, with the economic, social and environmental damage irreparable. Studies reviewed evidenced the importance of hybrid renewable energy systems in bridging the power supply and demand gap in emerging markets considering cost savings and emissions reduction. None of the studies paid attention to the importance of social action (responsibility) in implementing power system solutions. Especially pertinent to prioritising environmental gains over economic gains.

Secondly, with the knowledge that the viability of power system solutions against techno-economic, environmental and social metrics is closely aligned to the optimisation of their designs and/or operations, a significant portion of HRESs design and operations analyses in the literature review, applied the energy systems modelling software HOMER in their analysis. This study intends to diversify the methods adopted in the power systems design optimisation reviewed in the literature, by implementing a numerical simulation method in comprehensively and rigourously validating results obtained in a previous study on HRES solutions [100]. This supports the transfer of knowledge, particularly in emerging markets where the cost of securing an academic (or personal) license for energy modelling and analysis software could be prohibitive.

7.3. Method

A systems elimination method was adopted for this study. Numerical simulation in Matlab was applied using equations (1 – 6). The cost function equations have been deduced from the equations of the straight line graph of solar-PV and energy storage system capacities (in the range of 0 – 100 kW and 0 – 82 kWh respectively) quantitatively determined in the study in [100]. The generator system cost and emissions reduction function were based on iterative computations of the systems' capacities and frequency of usage, assuming a fixed reduction in costs per decrease in capacity size (0 – 15.5 kW). In this study, a search space of 20,200 IPS solutions was defined. This provides a comprehensive validation of results obtained from a recent study [100] on hybrid PV-centric power system solutions for commercial centres as well as varying the methods adopted for power systems operations analysis. The numerical simulation in this study is performed considering the solar resource for Abuja and the load profile of the commercial centre in [100]. A limitation to this approach i.e. using a static solar resource and load profile in analysing the commercial centre's operations and in realising a suitable power system solution that meets energy demand, is the inability to capture day-to-day or seasonal resource variation experienced in a typical year. As such, the optimality (best performing system) of the solution realised in this study is limited to the implementation of the approach.

7.3.1. Design consideration for power systems' performance analysis

7.3.1.1. Solar resource

The solar irradiation data used in this study was from Copernicus Atmosphere Monitoring Service (CAMS) at latitude - tilt angle (0º), specific to Abuja, Nigeria [73]. Abuja is positioned at geographical coordinates: latitude - 10ºN and longitude - 8ºE. This study worked with a single day (24hr) solar irradiation data based on the average daily solar irradiation for each month of the year for 2017. The solar-PV system sizing for the capacity range considered, was guided by working with the lowest average daily irradiation (4.45 kWh/m2/day) for the year (August), against the commercial centre's peak load day (Saturday).

7.3.1.2. Load demand determination

The load profile is that of Olowos plaza, a hypothetical commercial centre situated in Abuja, Nigeria, and is based on survey data of similar centres. The plaza has a weekly variable load demand, with the same total load demand from Monday – Friday (117 kWh per day), increased demand on Saturday (134 kWh) and reduced demand on Sunday (36 kWh). The total weighted average daily and weekly energy demand are 108 kWh and 757 kWh respectively. Average hourly energy demand is 4.5 kWh, base load is 0.4 kWh and weekly peak demand is 10.8 kWh. The base load cycle is from 22:00 hrs to 8:00hrs (Mondays – Saturdays) and from 18:00 hrs to 11:00 hrs on Sundays. Refer to Figure 6.5 for Olowos plaza weekly load demand.

7.3.1.3. Technologies considered

The systems technologies and operating conditions are captured in bullet points:

- Solar-Photovoltaic (PV) system – monocrystalline modules in 48V string array configurations were considered i.e. to limit the systems' current-carrying capacity, thereby limiting the systems' protection sizing.
- Energy storage system (ESS) – Rolls flooded, deep-cycle, lead-acid batteries were considered for the storage system technology [76]. A 50% depth of discharge, with a 13hr c-rate and multi-stage charging regime were also considered.

- Independent fossil fuel system (IFFS) – Diesel generators (DG) operating in prime power (indefinite running time) mode were considered for the generator system (GS).
- Balance of system (BOS) – that include (switchgears/system protection, charge controllers, inverters) supporting technologies for the solar-PV system and ESS were not independently considered. Although, their technical operating parameters, degradation, frequency of replacement and numerical efficiencies were considered for analysis.

7.3.2. Metrics considered for power systems' performance assessment

The numerical simulation process, explored a search space defined by three power system variables i.e. solar-PV, battery and DG capacities with maximum values of 100 kW, 82 kWh and 15.5 kW respectively. At one apex of the search space, the all renewable energy system (RES) implemented a solar-PV array design (100 kW) supported by battery storage (82 kWh) while at the other apex, the fossil fuel system (GS) was solely operating on a 15.5 kW DG. The search space was populated by implementing a step size iteration sequence (1 – 100%) from zero to the maximum capacities of the RES, GS, integrated hybrid solar-PV based system (IHSS = solar-PV + GS) and integrated hybrid solar-PV and battery based system (IHSBS = RES + GS). A search space of 20,200 (202 x 100) IPS solutions was realised by simulating all possible solutions (feasible and non-feasible) of the power system configurations (RES, GS, IHSS and IHSBS) considered. Feasible solutions were defined as the solutions that meet the commercial centres daily peak load demand, are within technical operating parameters (TOPs) and satisfy the metrics of affordability and sustainability i.e. cheapest lifetime costs ($/20 years) and lowest yearly CO_2 emissions. The non-feasible solutions are all solutions that do not meet the aforementioned conditions.

The systematic search implemented three orders of elimination in realising an optimum solution. The first order eliminated 15,250 IPS solutions for not meeting the commercial centre's average daily and peak load demand (basic power system operating requirements), reducing the search space to 4,950 IPS solutions. The second order eliminated a further 4,929 IPS solutions for not meeting TOPs, reducing the solutions in consideration to 21. The final order eliminated 20 IPS solutions in realising an optimum solution assessed against lifetime costs ($/20 years) and yearly GHG emissions (CO_2 tonnes/yr.).

7.3.2.1. Technical assessment (Reliability)

The technical assessment of power systems' performance being the second order of systems elimination, this considered TOPs in realising solutions that satisfied reliability metrics. TOPs are practical real-life considerations that aim to limit the system average interruption duration index (SAIDI) and system average interruption frequency index (SAIFI) to zero. Planned interruptions i.e. refuelling times and maintenance schedules are assumed to occur during non-commercial hours and do not interfere with the outcome of these reliability indexes (SAIDI and SAIFI). Therefore TOPs are:

- The minimum solar-PV capacity that is practical for a hybrid IPS (IHSS and IHSBS) mix;
- Diesel generator operating intensity;
- Maximum load demand in relation to diesel generator operating capacity;
- Duration of diesel generator operation at base load;
- Battery array configuration/matrix for the battery technology implemented (Rolls lead-acid battery).

Power system solutions are considered reliable if they can meet the conditions for TOPs i.e. ensuring the commercial centre's operation is seamless with no unmet load.

7.3.2.2. Economic assessment (Affordability)

The economic assessment was the third order of systems elimination but second priority level when assessed in tandem with the sustainability metric. Solutions in the power systems' search space (20,200 solutions), that returned lifetime costs lower than or equal to the base IFFS (≤ $189,000) and also satisfied technical operating parameters were considered. The equations applied for the economic assessment in this study were realised from power systems capacity sizing deduced from graphical representations and iterative computations. These equations encompass lifetime costs ($/20 years) implications for all IPS solutions evaluated. The equations are:

Economic cost as a function of power system capacity

$C_{solar\text{-}PV} = 1937.1x + 2895.9$ (1)
$C_{ESS} = 8171.4y + 1177.9$ (2)
$C_{GS} = (189 \times 10^3)\ z$ (3)

Where:

$C_{solar\text{-}PV}$: solar-PV system's lifetime costs ($/20 years);
C_{ESS}: energy storage system's lifetime costs ($/20 years);
C_{GS}: generator system's lifetime costs ($/20 years);

x: solar-PV system capacity;
y: energy storage system capacity; and
z: is the percentage increment (1-100%) in the iteration sequence that corresponds to an IPS system capacity in the range i.e. 1% = least cap, 100% = max cap.

In light of the above, the economic element for the four categories of power system solutions considered were realised based on the following combination of equations:

- RES = Eqs. (1 + 2)
- GS = Eq. (3)
- IHSS = Eqs. (1 + 3)
- IHSBS = Eqs. (1 + 2 + 3

7.3.2.3. Environmental assessment (Sustainability)

The environmental assessment was also the third order of systems elimination, but first priority level when assessed in tandem with the affordability metric. Solutions in the power systems' search range (20,200) greater than or equal to 0 CO_2 tonnes/yr. – baseline GHG emissions were considered. Also considered, were solutions less than 46 CO_2 tonnes/yr. – baseline GHG emissions of the primary GS.

That is, $0 \leq$ emissions target < 46. The equations applied for the environmental assessments were predicated on the capacities in the GSs' range and the frequencies of their daily usage. The equations formulated applied to all power system solutions under the GS, IHSS and IHSBS umbrella, excluding those under the RES category i.e. 0 CO_2 tonnes/yr. The equations for the IPS solutions analysed are:

Emissions reduction as a function of frequency of system usage

$$\mathcal{E}_{GS} - 46z \tag{4}$$

$$\mathcal{E}_{IHSS} - 46z \times 0.75 \tag{5}$$

$$\mathcal{E}_{IHSBS} - 46z \times 0.5 \tag{6}$$

Where:

$\mathcal{E}_{GS}$: the GS's yearly GHG emissions (CO_2 tonnes/yr.);
$\mathcal{E}_{IHSBS}$: the IHSBS's yearly GHG emissions (CO_2 tonnes/yr.);
$\mathcal{E}_{IHSS}$: the IHSS's yearly GHG emissions (CO_2 tonnes/yr.);

z: is the percentage increment (1-100%) in the iteration sequence that corresponds to an IPS system capacity in the range i.e.1% = least cap, 100% = max cap;
0.75: avg. frequency of usage i.e. the GS meets ¾ of daily load demand;
0.5: avg. frequency of usage i.e. the GS meets ½ of daily load demand.

The flowchart in Figure 7.3 illustrates the search sequence implemented in realising an optimal IPS solution based on all the power system assessments described in this section.

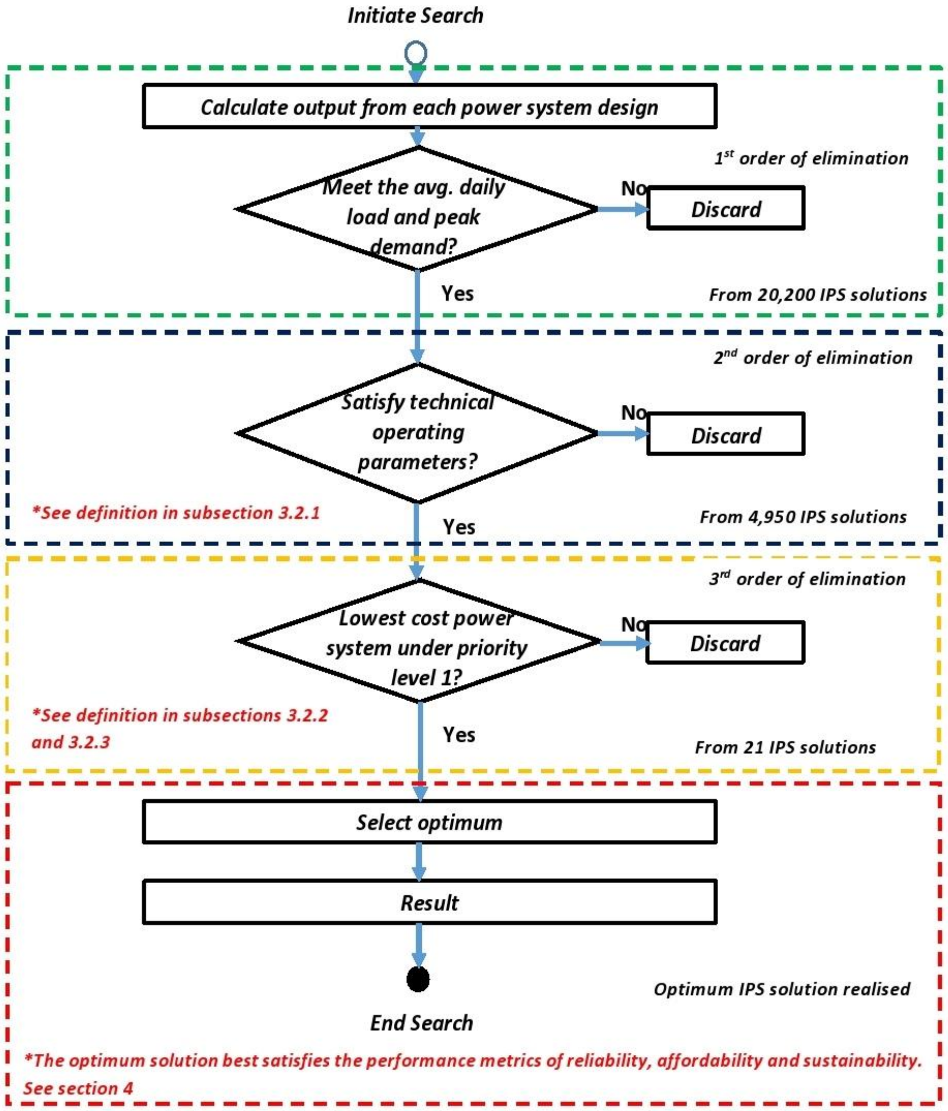


Figure 7.3 – Flowchart of the systematic search implementation on IPS solutions

7.4. Results

7.4.1. Categorisation of all solutions

Table 7.1 indicates all power system solutions categorised according to their lifetime cost ($/20 years) implications, with Table 7.2 indicating all power system solutions categorised according to their yearly GHG emissions (CO_2 tonnes/yr.). These tables account for the entire search space of 20,200 IPS solutions.

Table 7.1 – Numbers of IPS solutions categorised by their lifetime cost implications

Lifetime cost	**Integrated Power Systems (IPS)**			
Cost ($/20 years)	RES	GS	IHSS	IHSBS
> 850,000	3	0	0	393
800,000 – 849,000	5	0	0	597
750,000 – 799,000	6	0	0	508
700,000 – 749,000	6	0	0	598
650,000 – 699,000	6	0	0	598
600,000 – 649,000	6	0	0	598
550,000 – 599,000	5	0	0	507
500,000 – 549,000	6	0	0	598
450,000 – 499,000	6	0	0	598
400,000 – 449,000	6	0	0	598
350,000 – 399,000	5	0	0	597
300,000 – 349,000	6	0	268	509
250,000 – 299,000	6	0	1187	598
200,000 – 249,000	6	0	2113	598
150,000 – 199,000	6	21	2593	598
100,000 – 149,000	5	27	2187	597
< 100,000	11	52	1652	910
Total IPS	**100**	**100**	**10000**	**10000**

Table 7.2 – Numbers of IPS solutions categorised by their yearly GHG emissions (CO_2 tonnes/yr.)

IPS	**Emissions – CO_2 (tonnes/yr.)**															
	46	**45**	**44**	**43**	**42**	**41**	**40**	**39**	**38**	**37**	**36**	**35**	**34**	**33**	**32**	**31**
RES	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GS	2	2	2	2	2	2	3	2	2	2	2	3	2	2	2	2
IHSS	0	0	0	0	0	0	0	0	0	0	0	100	200	300	300	300
IHSBS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

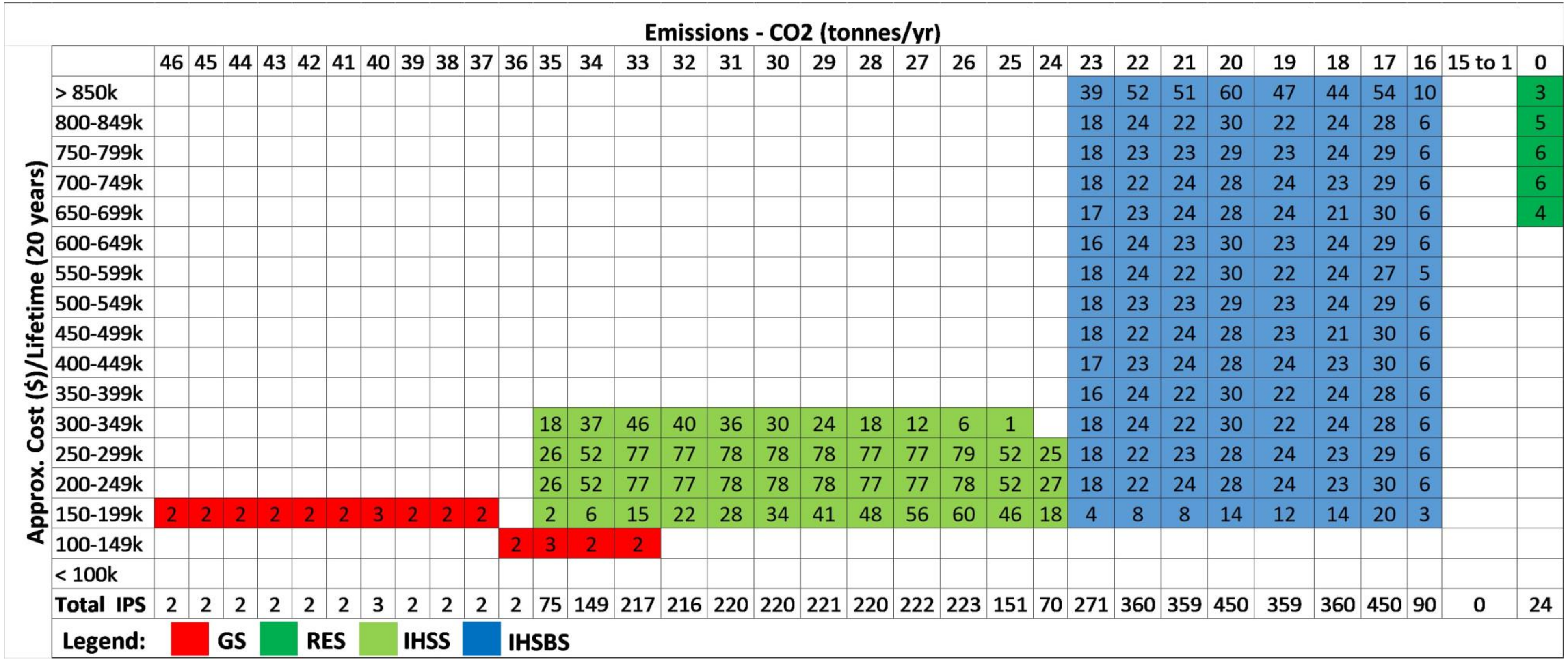
IPS	**Emissions – CO_2 (tonnes/yr.)**															
	30	**29**	**28**	**27**	**26**	**25**	**24**	**23**	**22**	**21**	**20**	**19**	**18**	**17**	**16**	**15**
RES	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GS	2	3	2	2	2	2	2	3	2	2	2	2	2	3	2	2
IHSS	300	300	300	300	300	200	300	300	300	300	300	300	300	300	300	200
IHSBS	0	0	0	0	0	0	0	300	400	400	500	400	400	500	400	400

IPS	**Emissions – CO_2 (tonnes/yr.)**															
	14	**13**	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**0**	**Total**
RES	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100
GS	2	2	3	2	2	2	2	2	3	2	2	2	2	3	0	100
IHSS	300	300	300	300	300	300	300	300	300	200	300	300	300	400	0	10000
IHSBS	500	400	500	400	400	500	400	400	500	400	400	500	400	600	0	10000

7.4.2. Categorisation of theoretical solutions – 2nd order of systems elimination

Table 7.3 represents the theoretical power system solutions, i.e. the power system solutions that meet the average/hr daily load demand and/or peak load demand but do not satisfy TOPs. The theoretical solutions are categorised according to their lifetime costs ($/20 years) and yearly GHG emissions (CO_2 tonnes/yr.)

Table 7.3 – The 4,950 theoretical IPS solutions categorised by their lifetime cost implications ($/20 years) and yearly GHG emissions (CO_2 tonnes/yr.)



Approx. Cost ($)/Lifetime (20 years)	Emissions - CO2 (tonnes/yr)																																
	46	45	44	43	42	41	40	39	38	37	36	35	34	33	32	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15 to 1	0
> 850k																								39	52	51	60	47	44	54	10		3
800-849k																								18	24	22	30	22	24	28	6		5
750-799k																								18	23	23	29	23	24	29	6		6
700-749k																								18	22	24	28	24	23	29	6		6
650-699k																								17	23	24	28	24	21	30	6		4
600-649k																								16	24	23	30	23	24	29	6		
550-599k																								18	24	22	30	22	24	27	5		
500-549k																								18	23	23	29	23	24	29	6		
450-499k																								18	22	24	28	23	21	30	6		
400-449k																								17	23	24	28	24	23	30	6		
350-399k																								16	24	22	30	22	24	28	6		
300-349k												18	37	46	40	36	30	24	18	12	6	1		18	24	22	30	22	24	28	6		
250-299k												26	52	77	77	78	78	78	77	77	79	52	25	18	22	23	28	24	23	29	6		
200-249k												26	52	77	77	78	78	78	77	77	78	52	27	18	22	24	28	24	23	30	6		
150-199k	2	2	2	2	2	2	3	2	2	2		2	6	15	22	28	34	41	48	56	60	46	18	4	8	8	14	12	14	20	3		
100-149k											2	3	2	2																			
< 100k																																	
Total IPS	2	2	2	2	2	2	3	2	2	2	2	75	149	217	216	220	220	221	220	222	223	151	70	271	360	359	450	359	360	450	90	0	24

Legend: 🟥 **GS** 🟩 **RES** 🟩 **IHSS** 🟦 **IHSBS**

7.4.3. Categorisation of practical solutions – 3rd order of systems elimination

Table 7.4 breaks down the technical composition, environmental and economic implications of the practical IPSs. Although, the base RES and GS systems are unviable when evaluated against economic and environmental factors in tandem, they are included in Table 7.4 as reference systems for perspective.

Table 7.4 – A breakdown of the Practical IPS solutions and reference systems' capacities against their technical compositions, environmental and economic implications

Power System	**Capacity**			**Implication**	
	Solar-PV (kW_p)	Battery (kWh)	Diesel Generator (kW)	Environmental (CO_2 tonnes/year)	Economic ($/20 years)
RES100	100	82	-	0	867,000
GS15.5	-	-	15.5	46	189,000
IHSS44	44	-	11	24	189,000
IHSS43	43	-	11	24	187,000
IHSS42	42	-	11	24	185,000
IHSBS13	13	9	11	16	183,000
IHSS41	41	-	11	24	183,000
IHSS40	40	-	11	24	181,000
IHSS39	39	-	11	24	179,000
IHSS38	38	-	11	24	177,000
IHSS37	37	-	11	24	175,000
IHSBS12	12	9	11	16	175,000
IHSS36	36	-	11	24	173,000
IHSS35	35	-	11	24	171,000
IHSS34	34	-	11	24	169,000
IHSS33	33	-	11	24	167,000
IHSBS11	11	9	11	16	166,000
IHSS32	32	-	11	24	165,000
IHSS31	31	-	11	24	163,000
IHSS30	30	-	11	24	161,000
IHSS29	29	-	11	24	160,000
IHSS28	28	-	11	24	158,000
IHSS27	27	-	11	24	156,000

7.4.4. Optimum power system solution – 3rd order of systems elimination (1st priority level)

Table 7.5 highlights the optimal IPS solution (with a lifetime cost of $166,000 and 16 CO_2 tonnes in yearly GHG emissions) amongst the practical and reference power system solutions. The table accounts for the 21 practical solutions assessed against the reference systems – GS (with lifetime cost of $189,000 and 46 CO_2 tonnes in yearly GHG emissions and the RES (with lifetime cost of $867,000 and zero yearly emissions), at both ends of the table. The metric for assessing affordability (economic viability) is represented on the vertical axis with that of sustainability (environmental viability) on the horizontal axis. The optimum power system solution is highlighted in Table 7.5.

Table 7.5 – Optimal IPS solution based on the performance metrics of affordability and sustainability

Economic viability (2nd)

	Environmental viability (1st)				Ref – **Reference** IPS i.e. the RES and GS
Lifetime cost	Emissions – CO2 (tonnes/yr.)				
Cost ($/20 years)	46 (Ref)	24	16	0 (Lwst)	
> 850k (Ref)				◇	
189,000 (Ref)	□	+			
188,000					
187,000		+			
186,000					1st – **Principal** priority level
185,000		+			
184,000					
183,000		+	○		
182,000					
181,000		+			
180,000					
179,000		+			2nd - **Secondary** priority level
178,000					
177,000		+			
176,000					
175,000		+	○		
174,000					
173,000		+			
172,000					Opt – **Optimum** IPS solution (1st priority level, lowest cost option)
171,000		+			
170,000					
169,000		+			
168,000					
167,000		+			
166,000			○(Opt)		
165,000		+			Lwst -IPS with **lowest** lifetime costs or yearly GHG emissions
164,000					
163,000		+			
162,000					
161,000		+			
160,000		+			
159,000					
158,000		+			◇ RES
157,000					□ GS
156,000 (Lwst)		+			+ IHSS
Total IPS	**1**	**18**	**3**	**1**	○ IHSBS

7.4.5. Summary of results

Results from this study have demonstrated the IHSBS (solar-PV – 11 kWp; battery storage – 9 kWh and DG – 11 kW) as the best performing system (against the impact metrics of sustainability, affordability and reliability) in meeting the load demand of commercial centres in Nigeria. This evidences the viability of implementing an environmentally focused hybrid renewable energy system in bridging the electrification gap in access-deficient regions. This brings to the fore, the role of social action/responsibility in driving environmentally cleaner power system solutions. This is of particular importance as economic cost savings remain the priority consideration when implementing power system solutions.

The IHSBS was the optimum power system solution i.e. the lowest cost power system under priority level 1. It was more economically viable than 67% of power system solutions under priority level 2. The IHSBS had a comparative advantage of 81% and 12% in cost savings over the RES and GS respectively, for their operational lifetime (20 years). The system recorded a 65% reduction in yearly GHG (CO_2 tonnes/yr.) emissions over the GS. When compared to its closest competitor – the IHSS (solar-PV – 27 kWp and DG – 11 kW), the IHSBS was 6% costlier than the IHSS over their operational lifetime (20 years) but recorded a 33% reduction in yearly GHG emissions over same. It also had a better system's operations efficiency over the IHSS (closely matched supply-demand ratio). The IHSBS had a load factor (LF) of 90%, 24% more than the IHSS with a LF of 66%.

Introducing a carbon tax of $25 per tonne of CO_2 emitted [85] and unifying the metrics of affordability and sustainability, the IHSBS was still 4% costlier than the IHSS for their operational lifetime. These results evidence that carbon taxation (based on the current pricing structure) is not an effectual policy in mitigating the impact of climate change on our environment. Results infer that lifetime cost implications are sensitive to an increase in the percentage share of RE contribution (particularly the ESS capacity) in the hybrid mix. The increase in RE contribution also significantly reduces the yearly GHG (CO_2 tonnes/yr.) emissions by reducing the operating intensity of the GS. This also establishes the link between lifetime cost implications and a reduction in yearly GHG emissions.

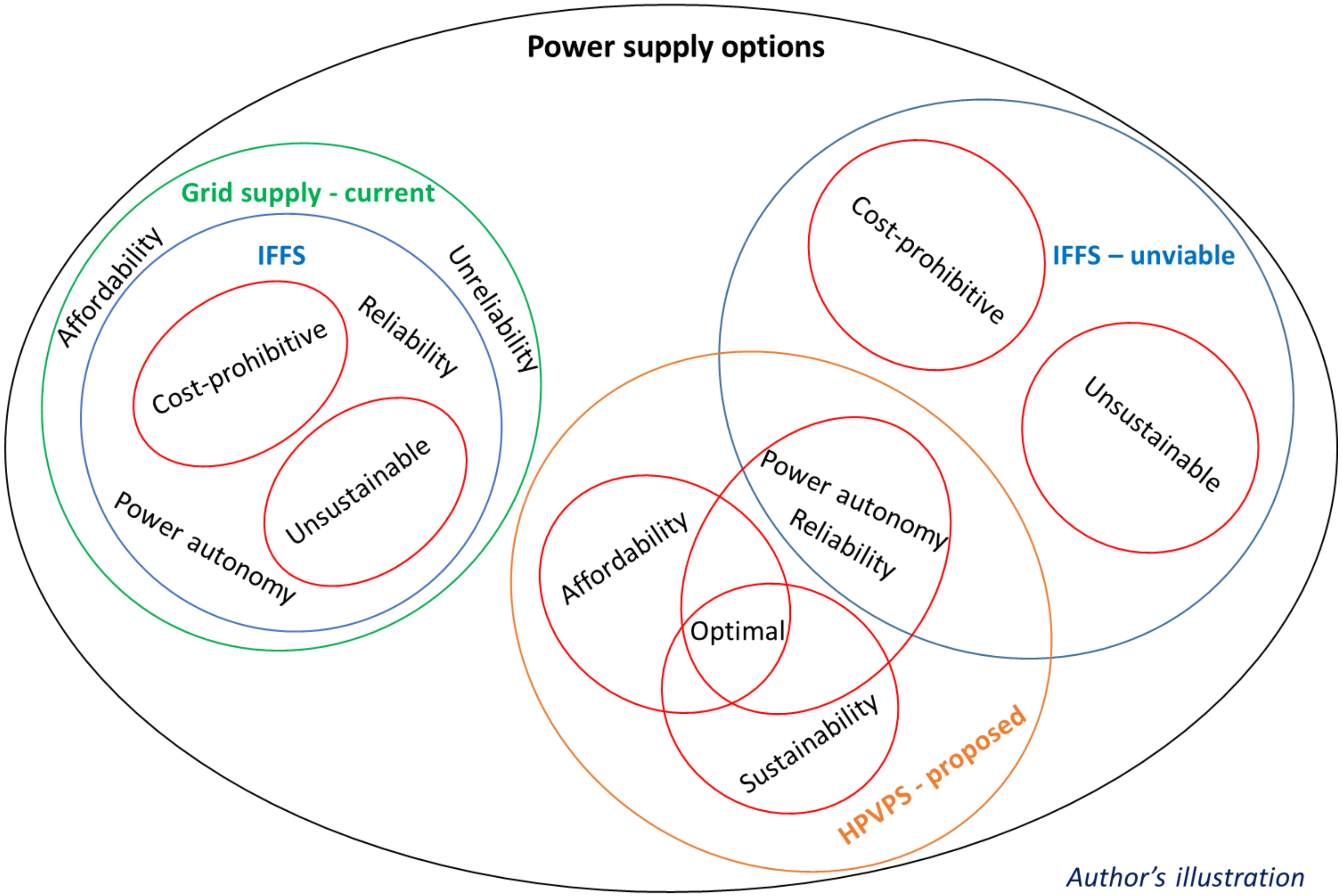
The findings of this study consolidates the viability of strategically electrifying commercial centres through hybrid photovoltaic-centric power systems (HPVPSs). Figure 7.4 illustrates the benefits of a HPVPS option amidst grid unreliability and implementing IFFS alternatives. The illustration highlights the current system of grid power supply complemented with the sub-optimal operation of IFFS. It also elicits the unviability of IFFS in sole operation due to cost implications and adverse environmental impact. Finally, the ideal power system configuration for the energy consumer is presented as the optimised operation of a PV system and IFFS in a hybrid system. This solution would offer the consumer lifetime benefits of reliability, affordability, sustainability and power system autonomy.

IFFS – Independent Fossil Fuel System e.g. diesel and petrol generators

HPVPS – Hybrid Photovoltaic-centric Power System – **a type of Hybrid Renewable Energy System (HRES)**

Notes

- ☐ Grid supply is unreliable so it is complemented by IFFS
- ☐ IFFS in sole operation is unviable
- ☐ HPVPS is proposed



Author's illustration

Figure 7.4 – Euler diagram highlighting the benefits of a hybrid photovoltaic-centric power system (HPVPS) option

7.5. Discussion

The IHSBS was 4% costlier than the IHSS over their lifetimes (when the metrics of affordability and sustainability were unified). However, the 33% reduction in yearly GHG emissions of the former power system solution over the latter, favours the implementation of the IHSBS for commercial centres in Nigeria. The IHSBS (90% LF) was also a better self-consuming system than the IHSS (66% LF). This is as a result of the integration of an ESS in the IHSBS. The exclusion of an ESS from the IHSS meant that the system generated excess energy, 24% more than the IHSBS. This translated to wasted energy, owing to the underdevelopment of a transactive electricity market (TEM) in Nigeria. As such, the IHSBS was a better performing system in matching daily energy production with the commercial centre’s energy demand.

The results from this study have shown the superior performance of PV-Battery-Diesel hybrid power systems over IFFSs against the impact metrics of affordability and sustainability. It also shows the added benefits of reliability and power supply autonomy for these hybrid power systems over conventional power grid systems [84, 94]. The optimal system in this study, the IHSBS, better sized the capacity of its ESS (reduced capacity size by 3 kWh) and DG (reduced capacity size by 4.5 kW) components in comparison to the “IHSBS 2” in [100]. Furthermore, the system had a lifetime cost reduction of 30% over same. Consolidating the statement that optimising the ESS component of the power system solution, taking into consideration capacity sizing and the operation strategies implemented could realise environmentally cleaner IPS with economic viability. Overall, these results highlight efforts towards ensuring access to affordable, reliable, sustainable and modern energy for all. These results bring third generation hybrid power systems to the fore in driving sustainable electrification and creating a sustainable environment for emerging economies. An enabling environment is a requisite in fostering the proliferation of these technologies. For example, the imposition of a 10% tax duty on solar modules in Nigeria [104] (an import-dependent economy) could inhibit this.

Optimising these hybrid power systems for a favourable environmental impact still realises economically viable systems. The 4% difference in costs that makes the environmentally optimised power system (IHSBS) costlier than the economically optimised system (IHSS) over their lifetime is considered insignificant. This is especially so, as some of these systems lose substantial sums when they are deployed sub-optimally in operation. The 4% added cost is also considered an investment (social action) in supporting the global drive on deeply decarbonising the environment. As some technologies (carbon capture, storage and sequestration) may still take years to upscale in the fight against climate change, highlighting the importance of social responsibilities i.e. relatively higher power systems development costs (with increased environmental and social benefits) could offer long-term economic gains and be pivotal in realising environmental targets and meeting nationally determined contributions (NDC). This would be considered as such until energy and particularly climate policies (such as carbon taxation) are designed to adequately tackle the possible long-term economic implications of implementing non-environmentally focused HRESs.

Therefore, the conscious decision to implement environmentally clean HRESs lies with the power project owners/developers. In emerging economies, social action could be the responsibility of the individuals/sectors implementing energy autonomous solutions.

7.6. Conclusions

This study has validated the performance of scalable hybrid PV-centric power systems over IFFS solutions for the C&I sectors. The results found distributed sustainable energy solutions offered the same benefits of power autonomy and reliability as IFFSs but with the added benefits of affordability and sustainability. The IHSBS was the optimum power system solution when assessed against the three impact metrics (affordability, reliability and sustainability). The IHSBS was also the better self-consuming system with a 90% LF compared to the IHSS with a 66% LF. The implementation of power system solutions with significant consideration for environmentally clean solutions could boil down to social responsibility borne by the project developer. Social action could yet be an area of consideration in combatting climate change whilst technology is emerging. These technologies could take years to upscale to a level of significant impact in the battle against climate change.

The results were able to demonstrate that a more impactful approach towards realising holistic power system solutions for emerging economies was in evaluating the equal importance of socio-environmental factors with economic factors. Creating an enabling environment (through policies and regulations i.e. the development of TEM) that facilitates the proliferation of third generation hybrid power systems (with increased RE penetration) in emerging economies presents a viable approach in mitigating the impact of climate change on our environment. These could be more effective than carbon taxation (based on the current pricing structure) and outright bans on IFFS in access-deficient regions.

Findings from this study established a relationship between lifetime cost implications and the percentage share of RE contribution in HPVPSs. It further elicited the relationship between lifetime cost implications and yearly GHG emissions reduction. A limitation of this study was the fact that a sensitivity analysis was not carried out to explore these findings in detail. Further research on our part, will focus on the shift from third generation hybrid power systems to fourth generation hybrid power systems that eliminate diesel generators using electric vehicles (EVs) for enhanced energy storage.

CHAPTER EIGHT

Conclusions

8.1. Theoretical and Practical contributions

> ***"Mr A: Light never comot since morning? – You haven't experienced power outage all day?"***
>
> ***"Mrs B: O boy! Dem no dey carry light again o. Na the new Nigeria we dey so ooo –***
> ***We no longer experience outages. Welcome to the new Nigeria!"***
>
> ***– Conversations (in Pidgin English) I hope would become the norm in Nigeria's near future***

The theoretical and practical contributions of this thesis are discussed in the subsections that follow:

8.1.1. Theoretical contributions

This thesis contributes theoretically to the body of knowledge and by extension Nigeria's electrification plan through the research approach adopted and the methods followed. Studying the theory (see chapters Six and Seven) before proffering data-driven practical solutions (see chapters Four, Five, Six and Seven) ensured that the results realised were predicated on data analytics informed by relevant theories and not arbitrarily derived. This advances the research approach of balancing an understanding of theories with the application of data analyses. It ensured that representative data were sourced and analysed in order to realise solutions with real life applications.

The case studies in chapters Six and Seven, consolidate the application of optimisation techniques to create practically achievable and affordable renewable energy systems. This thesis primarily focussed on optimising the decision making process – identifying the most viable power system solution (guided by the impact/performance metrics of affordability, reliability and sustainability) to be implemented across multiple sectors in Nigeria. Some of the other factors that could present as independent optimisation problems were encapsulated by the performance metrics as well as informed indirectly through the decision making process. They include:

- Scheduling – what system (e.g. solar-PV, diesel generator, petrol generator and batteries) in the HPVPS was scheduled to meet the load demand at any given time during an operation cycle (24 hours)?
- Resource allocation – Based on scheduling, how could resources (natural, technical, human and financial) be adequately harnessed and/or allocated

towards sustaining the HPVPS’s operations without unnecessary interruptions?

8.1.2. Practical contributions

This thesis contributes practically to the body of knowledge by informing policy formulation, action and direction. Results from the studies in chapters Six and Seven highlight the importance of a more defined climate policy. It presents the fact that carbon taxation and outright bans on diesel/petrol generators might not be the most effective policies in mitigating the impact of GHG emissions on our environment. Policies that incentivise the proliferation of third generation HPVPS across the multi-sectors could be more beneficial in supporting climate change mitigation efforts.

Studies in chapters Six and Seven highlight the integration of predictive and preventive maintenance (PdM and PM) in HPVPSs as essential in maintaining systems performance over their lifetime. PdM and PM is important in reducing or eliminating the need for corrective maintenance (CM). By implementing decentralised power solutions defined by maintenance schedules (PdM and PM), a culture of systems maintenance is permeated in the power sector that could extend to the multi-sectors. Also, local content development is supported through investments in technical capacity realised with every HPVPS deployed for operation in Nigeria.

The results in this thesis also support energy efficiency (EE) policy targets. The power system solutions realised in chapters Six and Seven elicited the relationship between facility management (FM) and EE. Through a bottom-up approach, results from chapters Six and Seven evidence the viability of implementing buildings/facilities designed around their HPVPSs underpinned by EE realised through FM. This thesis also highlighted the relationship between EE and renewable energy (RE).

8.2. Implications of the research approach

A mixed methods approach (qualitative analysis, quantitative analysis, and numerical simulation) ensured that this thesis presented a body of work with original content and analytical base. It also enabled results attained to be validated by more than one method. A balance of understanding the relevant theories in the subject studied and the application of data analyses in finding solutions to problems presented, helped in establishing a link between research and industry. The research approach also guided the direction of the research process, presenting a body of work that is structured and forms a cohesive whole.

Chapter Four worked with electricity costs data sourced from NEMSA, via their collaboration with German development partners (GIZ), active in Nigeria's energy sector through their Nigerian Energy Support Programme (NESP). This highlights the link between research and industry. Electricity costing data from Nigeria's industrial sector were analysed with results highlighting the economic cost of unreliable power supply to Nigeria. The research process followed in chapter Four initiated a research chain where industrial practices informed a study that presented a nationwide problem in quantifiable terms. Quantitative data is a more reliable and compelling reference in guiding policy actions.

Based on the study of relevant theories and an overview of Nigeria's energy sector in chapter Two, an idea of the most pragmatic solution to Nigeria's electricity problem presented in chapter Four was analysed in chapter Six with focus on optimising its power generating potential. The interviews and surveys presented in chapter Five introduced a social element to the research through the data realised. The approach was able to scale down the socioeconomic impact of power supply unreliability in Nigeria to smaller commercial centres and all the way to personal levels (this also allowed for comparison and contrasting). The rationale was that the residential sector housed the workforce of all other sectors, this therefore informed the decision to survey the residential sector.

Chapter Six presented practical solutions to Nigeria's electricity problem. The solution realised was a four pronged fork that addressed technical, economic, environmental and social issues in one sitting. The case study approach adopted for chapters Four and Six enabled the thesis to isolate problems for deeper analysis, preventing an unwieldy or sprawling approach. Chapter Seven validated the method proposed in chapter Six thereby corroborating the results realised in same. It also discussed the application of the power system solutions realised beyond the case study scenario presented in chapter Six. The results realised in chapter Six and verified in chapter Seven had implications that tied into advancing the cause of six of the seventeen United Nation's Sustainable Development Goals. Hybrid renewable-centred systems with only minimal backup from petrol or diesel generator sets can simultaneously deliver deep decarbonisation benefits to Nigeria, improved reliability of power supply to the country's vital multi-sectors, improved quality of life through better air quality and socioeconomic development, all at lower lifetime costs than currently used systems.

The thesis progresses from presenting the problem of countrywide unreliable power supply to realising viable solutions that informs policy action and direction. It tells a story of Nigeria's unreliable power supply at different socioeconomic levels and from different perspectives.

8.3. How the thesis answers the research questions and meets the objectives

8.3.1. Research questions

i. *What is the economic, environmental and social cost of unreliable power supply to Nigeria?* The thesis answers these questions in chapters Four, Five, Six and Seven. The economic cost of unreliable power supply was presented through the industrial sector case study in chapter Four. The impact of unreliable power supply on businesses and their operations were analysed and discussed. The findings of the study presented the enormity of the cost incurred in deploying alternative energy solutions i.e. IFFSs (diesel and petrol generators) in addressing the unreliable power supply. This was also considered unfavourable for the growth and development of the sector. The environmental cost of the current power systems (grid plus IFFS) were evaluated by the potential GHGs emitted from these systems in operation. The economic cost for small to medium businesses were covered in chapter Five through the social studies undertaken. The interview based social study elicited the impact of unreliable power supply as lost business opportunities and increased cost of running businesses. The study established a link between the economic impact of unreliable power supply to the business owner and on quality of life. Reduced quality of life was considered a social cost from unreliable power supply that could arise from stressing and worrying about business profitability. The second social study corroborated the economic findings by surveying opinions on the countrywide power supply situation. The survey elicited people's preferences in cutting the cost of running IFFSs amidst grid unreliability. They favoured alternative energy (RE) solutions, provided they were more affordable and reliable than their current power systems. Chapters Six and Seven through a comparison of alternative energy solutions (HRES), presented the lifetime economic benefit of deploying HRES solutions when compared to IFFSs. The studies also established nine of the fourteen energy autonomous solutions analysed as more economical than the current system (grid plus IFFS). This was measured by LCOE and analysed through a LCCA. The environmental cost of IFFSs in operation were also presented and evidenced in comparison to HRESs and RESs solutions in operation. This was measured through yearly GHG (CO_2) emissions.

ii. *How can the gaps identified in the country's electrification agenda be addressed towards driving economic, environmental and social sustainable development?* The thesis answers these questions through the solutions analysed and discussions presented in chapters Six and Seven. Through the energy solutions presented, economic, environmental and social sustainability can be advanced. These are realised through a more defined climate policy (environmental implication) that allows for the development of TEM and the deregulation of the electricity market (the pervasion of HRESs solutions and energy trading). In creating an enabling environment for energy trading, more electrification pathways that could accelerate countrywide electrification were explored. This also addresses power supply unreliability and its impact on business operations. Countrywide available and accessible power supply could spur economic activities (economic growth and development). Energy trading facilitated by policy actions, would empower excess generators to extend electricity supply to unserved and underserved communities/sectors (residential) countrywide. This presented the idea of community energy and blended finance (crowd funding – residents in residential estates monetary contributions). The pervasion of HRES is an example of alternative power system solutions. Social integration and development, would be a result in part of the implementation of the power system solutions presented, analysed and discussed. Formulating policies around the implementation of these solutions and enforcing same as discussed in these chapters, present a viable way of addressing economic, environmental and social sustainable development. Emodi *et al.*'s [146] study emphasised the importance of a defined climate policy in Nigeria. This findings of their study was in line with this thesis's areas of focus (particularly the environment aspect). This thesis went further to elicit ways by which viable energy solutions can help in formulating climate policies. Adhekpukoli [66] presented the democratisation of Nigeria's electricity sector i.e. the deregulation of the sector to accommodate disparate solutions, in improving the country's electricity crisis. The electrification pathways presented in this thesis supported the idea. Wojuola and Alant's [64] study identified a general lack of awareness of RETs among Nigerians. They concluded that awareness programmes and initiatives should encompass all knowledge delivery systems (formal and informal education). This thesis corroborated their findings by also studying Nigerians awareness on RETs. It went further by eliciting a probable link between unreliable power supply and social costs i.e. adverse human health.

8.3.2. Research objectives

- *Raising technical awareness on Nigeria's electricity situation by undertaking studies guided by the pillars of economic, social and environmental performance.* This objective was met through the studies in chapters Four – Seven and the analyses of power systems' solutions in chapters Six and Seven. The problems of countrywide unreliable power supply were presented. Their bearings on economic, social and environmental performance, were also analysed and discussed.

- *Proposing practical solutions to increasing and sustaining Nigeria's electric power supply availability and accessibility with focus on driving economic, social and environmental sustainable development.* The electrification pathways presented in chapters Six and seven addressed this objective. The development of an energy autonomous multi-sector through the implementation of HRESs and the extension of power supply access to unserved/underserved communities from their excess generation were the electrification pathways presented. With the latter pathway facilitated by the development of TEM. These discussions were covered in chapter Six.
- *Using photovoltaic (PV) resource data and demand profiles to simulate a large suite of potential solar-PV-Diesel Generator (DG) hybrid solutions and select the best-performing from economic, environmental perspectives, while satisfying user requirements.* Chapters Six and Seven carried out an analysis of power system solutions based on country-specific solar resource data (simulated on CAMS) and demand profiles (realised through surveys) of commercial centres. The solutions realised were evaluated for performance considering metrics of reliability (no unmet load), affordability ($/20 yrs.) and sustainability (CO_2 tonnes/yr.).
- *Exploring the application of such solutions given Nigeria's resource base (natural resource i.e. abundant sunlight) and economic potential.* Chapters Four and Five covered the electricity supply problem at scale and people's opinions of power supply unreliability on their lives and livelihood. These informed possible power system solutions. A review of relevant literature in chapter Six supported the power system solutions explored to address the power supply unreliability. Chapters Six and Seven analysed these solutions, highlighting Nigeria's abundant solar resource and the positive impact countrywide electricity supply access (quantity and quality of supply) could have on the economy.
- *Concluding with proposals for change that have an analytical basis.* The policy (climate and energy) conclusions were based on the results of the

analysis carried out in chapters Four – Seven. Particularly chapters Six and Seven.

Èkọ́ Layé (Yoruba) – Research is Life

The Author

8.4. The way forward – some recommendations

- It is imperative that the inter-ministerial committee that oversaw the realisation of policy documents such as; NREEEP, NREAP, NEEAP and RESIP convenes towards developing a more defined climate policy that guides climate mitigation efforts at the national level;
- It is important that electrification goes beyond lighting and provides the quality of power required in sustaining a rise in economic activities. Therefore, the REA should review its electrification programmes and initiatives (NEP, EEI and EEP) to incorporate a structure that facilitates the scaling up of off-grid power system solutions being deployed for rural settlements, with a view that the productive use of electricity in newly electrified communities could substantially rise;
- It is also important that power system technologies deployed in off-grid sustainable solutions are harmonised to ease the possible interconnection of mini-grids serving multiple communities, the interconnection of mini-grids with the main grid and in emergency situations where a protective scheme deployed in another system has to be replaced in order to maintain uninterrupted power supply to a particular centre, community or institution. This can be achieved through the collaborative efforts of the Standards Organisation of Nigeria (SON), regulators in the power sector – NERC and technical enforcers in same - NEMSA ;
- Policy should be amended to facilitate the development of a transactive electricity market (TEM) in order to augment pathways for extending, increasing and improving countrywide electrification. The development of TEM would facilitate the implementation of initiatives like “Comtridential” and reverse “In-DisCos” discussed in chapters Six and Seven as pathways to extending, increasing and improving countrywide electrification. Policy mechanisms like

FIT, NEM and DSM would enhance the implementation and operation of TEM in a modified electricity market. As Nigeria transitions towards stable power supply and eventually uninterrupted power supply, DSM could help in increasing the daily centralised grid energy allocation to some sectors e.g. the informal sector (petty traders, roadside barbers, carpenters, craftsmen, etc.) that also contributes to the economy [137 – 138]. DSM would encourage optimising a balance of grid-connected supply with grid defected HPVPS for sectors (C&I and some residential buildings) that can afford to fuel stack;

- Nigeria's ministry of power and its parastatals should house a research for dissemination, development, deployment and demonstration (R4D) unit within their establishment. This unit can be saddled with the responsibilities of reviewing and collating energy research that this thesis would contribute as well as other research in the public domain pertinent to Nigeria and other developing countries' energy sector. This can be achieved by subscribing to publishers like Elsevier. Also the unit could be responsible for periodically auditing energy consumption in the multi-sectors in Nigeria. The data (becoming historical data over time) generated through these processes could inform policy action and direction, regulations, means of enforcement, advance research on energy requirements that are unique and specific to a community, an industry, a sector, a state, the country and the broader region;
- Personnel from the energy audit unit would also inspect and assess the extent to which the built environment i.e. existing buildings and buildings under construction are compliant with energy efficiency and conservation requirements stipulated in the national building code;
- The utility companies/energy service companies (DisCos) should ensure integrated resource planning (IRP) is incorporated into their business model (service delivery structure) to continually track, measure and evaluate the value being created/added to Nigeria's electricity supply industry (NESI).

Some of the socioeconomic and environmental benefits of uninterrupted power supply in Nigeria would be:

- the benefits on an individual level – widespread literacy, intellectually empowered individuals and improved quality of life;

- the benefits at a sectoral level – improved healthcare facilities, better academic institutions, good roads, socioeconomic growth, development and integration;
- the relationship between an individual's quality of life and sectoral performance – quality education develops a skilled and motivated workforce that contributes to the performance of the multi-sectors which aggregates to good socioeconomic and environmental performance of the broader country. This can be measured through indicators such as; GDP, life expectancy, employment rates, meeting policy targets, registered patents etc.

8.5. Further work

Life is a marathon not a sprint – unknown

In advocating a paradigm shift whereby the multi-sectors contribute to the power sector's effort in increasing countrywide electrification rates, there is an opportunity to create a sustainable environment by driving sustainable electrification. Therefore, further areas of research could include:

i. Studying the health implications of particulate matter/pollutants i.e. introducing another metric/cursor to the graph in Figure 6.11;
ii. Exploring how grid defected autonomous power producers like the C&I sectors can electrify the transportation sector in Nigeria through excess generation from hybrid renewable energy systems being directed to electric vehicles (EVs);
iii. Optimising solar-PV and solar-thermal for the pharmaceutical and hospitality industries (hotels and restaurants) in Nigeria.

Realising uninterrupted power supply in Nigeria requires the collective effort of government, public institutions, private institutions, industry, academia and development partners.

The marathon continues – Nipsey Hussle (2× Grammy award winning artiste)

References

[1] Olowosejeje, S., Leahy, P. and Morrison, A.P. (2019). The economic cost of unreliable grid power in Nigeria. *African Journal of Science, Technology, Innovation and Development.* 11 (2), pp. 1 – 11.

[2] FAO (2008). Climate Change and Food Security: A Framework Document. The United Nations, Rome. pp. 1 – 22.

[3] Reid, H and Swiderska, K. (2008). Climate Change – Biodiversity and Livelihood Impacts. *International Institute for Environment and Development (IIED)*. pp. 1 – 6.

[4] UAE (Ministry of Foreign Affairs) – Directorate of Energy and Climate Change (2012) *UAE Energy Outlook: Factors for global renewable energy roadmaps* [online] available from http://docplayer.net/39740922-Uae-energy-outlook-factors-for-global-renewable-energy-roadmaps-valletta-malta-5-september-2012.html [25th April, 2014]

[5] Presidential Task Force on Power (PTFP) (2015). The Transformation of Nigeria's Electricity Sector. Abuja: Treed Nigeria Media. pp. 22 – 85.

[6] Nigerian Electricity System Operator (2016) *Power Transmission Attains New Peaks of 5074.7MW & 109,372MW* [online] available from http://www.nsong.org/MediaPublicity/NewsDetails.aspx?NewsID=52 [19th February, 2016]

[7] Nigeria Population – Worldometers (2016) *Worldometers.Info* [online] available from http://www.worldometers.info/world-population/nigeria-population/ [24th February, 2016]

[8] GIZ-NESP (Deutsche Gesellschaft für Internationale Zusammenarbeit – Nigerian Energy Support Programme). (2015). The Nigerian Energy Sector (An Overview with a Special Emphasis on Renewable Energy, Energy Efficiency and Rural Electrification). 2nd ed. Abuja: *GIZ*. pp. 21, 22, 33 and 41.

[9] Creswell, J.W. (2014). Chapter One: The selection of a research approach. In: Creswell, J.W. Research design: qualitative, quantitative, and mixed methods approaches. *SAGE*. pp. 3 – 23.

[10]Forbes (2019) *Nigeria – Profile* [online] available from https://www.forbes.com/places/nigeria/ [25th January, 2019]

[11] Forbes (2019) *Aliko Dangote – CEO, Dangote Group* [online] available from https://www.forbes.com/profile/aliko-dangote/#4e73a58c22fc [25th January, 2019]

[12] Ugwu, H.U., Nwankwojike, B.N., Ogbonnaya, E.A. and Ekoi, E.J. (2012). Energy and Economic Losses Due To Constant Power Outages in Nigeria. *Nigerian Journal of Technology (NIJOTECH)* 31, pp. 186 -188.

[13] Proshare (2016) *Why companies will continue to leave Nigeria for Ghana* [online] available from https://www.proshareng.com/news/General/Why-companies-will-continue-to-leave-Nigeria-for-Ghana-/7324 [11th February, 2018]

[14] Clarke Energy (2008) *GlaxoSmithKline Captive Power Plant, Agbara, Nigeria* [online] available from https://www.clarke-energy.com/2008/glaxosmithkline-agbara-nigeria/ [3rd January, 2019]

[15] Coca-Cola Hellenic Bottling Company (2016) *Two new CHP plants in Nigeria* [online] available from https://coca-colahellenic.com/en/our-stories/two-new-chp-plants-in-nigeria/ [3rd January, 2019]

[16] Rates (2016) *Central Bank of Nigeria: Monthly Average Exchange Rates of the Naira*. [online] available from https://www.cbn.gov.ng/rates/exrate.asp?year=2015 [11th February, 2016]

[17] Nigeria Core Inflation Rate (2020) *Tradingeconomics.com*. [online] available from https://tradingeconomics.com/nigeria/inflation-cpi [4th March, 2020]

[18] Nigeria Interest Rate Forecast (2016) *Tradingeconomics.com*. [online] available from http://www.tradingeconomics.com/nigeria/interest-rate. [2nd December, 2016]

[19] Akpan, U., Essien, M. and Ishiak, S. (2013). The Impact of Rural Electrification on Rural Micro-Enterprises in Niger Delta, Nigeria. *Energy for Sustainable Development.* 17 (5), pp. 504-509. doi:10.1016/j.esd.2013.06.004.

[20] Oseni, M.O. (2016). Erratum To “Get Rid Of It: To What Extent Might Improved Reliability Reduce Self-Generation in Nigeria?” *Energy Policy.* 93, pp. 353-354. doi:10.1016/j.enpol.2016.03.035.

[21] Aliyu, A.S., Ahmad, T.R. and Muneer, A.S. (2013). Nigeria Electricity Crisis: Power Generation Capacity Expansion and Environmental Ramifications. *Energy.* 61, pp. 354. doi:10.1016/j.energy.2013.09.011.

[22] Nigeria Diesel Prices (2016) *Globalpetrpprices.com*. [online] available from http://www.globalpetrolprices.com/Nigeria/diesel_prices/ [4th April, 2016]

[23] Reuters (2017) *Nigeria's aims to diversify as 'era of oil booms' ends* [online] available from https://www.reuters.com/article/us-nigeria-oil/nigerias-aims-to-diversify-as-era-of-oil-booms-ends-idUSKBN1AB29R [30th November, 2018]

[24] Chete, L.N, Adeoti, J.O, Adeyinka, F.M, and Ogundele, O. (n.d). Industrial Development and Economic Growth in Nigeria: Lessons and Challenges. ADB Working Paper, wp/08. African Development Bank. pp. 1 – 37.

[25] Israel, G.D (2009). Determining Sample Size. Program Evaluation and Organizational Department: *Institute of Food and Agricultural Sciences (IFAS)*, University of Florida. pp. 1 – 5.

[26] Bartlett, J.E, Kotrlik, J.W and Higgins, C.C (2001). Organizational Research: Determining Appropriate Sample Size in Survey Research. *Information Technology, Learning and Performance Journal*. 19, pp. 43 – 50.

[27] National Population Estimates (2006). Population Forecasts 2006 – 2016. *Nigerian Bureau of Statistics*. Nigeria

[28] Encyclopaedia Britannica (2016) *Nigeria: Quick Facts* [online] available from http://www.britannica.com/place/Nigeria [10th January, 2016]

[29] World Weather and Climate Information (2016) *Nigeria: Average Weather and Climate in Nigeria* [online] available from https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine-in-Nigeria [15th January, 2016]

[30] Nigerian National Petroleum Corporation (2015) *Monthly Financial and Operations Report* [online] available from http://nnpcgroup.com/Portals/0/NNPC%20Monthly%20Financial%20%20Operations%20Report%20September%202015.pdf [30th January, 2016]

[31] Nigeria Unemployment Rate (2018) *Tradingeconomics.com*. [online] available from https://tradingeconomics.com/nigeria/unemployment-rate. [14th February, 2019]

[32] World of Maps.Net (2016) *Map of Nigeria: Map Population Density* [online] available from https://www.worldofmaps.net/en/africa/map-nigeria/map-nigeria-population-density.htm [23rd January, 2016]

[33] Nigeria Core Inflation Rate. (2016). *Tradingeconomics.Com*. [online] available from http://www.tradingeconomics.com/nigeria/core-inflation-rate. [14th February, 2016]

[34] National Renewable Energy and Energy Efficiency Policy (NREEEP). (2015). Federal Ministry of Power. Federal Executive Council, Nigeria.

[35] Ayodele, T.R., Ogunjuyigbe, A.S.O, and Amusan,T.O. (2016). Wind Power Utilization Assessment and Economic Analysis of Wind Turbines across Fifteen Locations in the Six Geographical Zones of Nigeria. *Journal of Cleaner Production.* 129, pp. 341-349. doi:10.1016/j.jclepro.2016.04.060.

[36] Ikejemba, E.C.X., and Schuur, P. (2016). "Locating Solar and Wind Parks in South-Eastern Nigeria for Maximum Population Coverage: A Multi-Step Approach". *Renewable Energy*. 89, pp. 449-462. doi:10.1016/j.renene.2015.12.024.

[37] Ajayi, O.O., and Ohijeagbon, O.D. (2015). Feasibility and Techno-Economic Assessment of Stand-Alone and Hybrid RE For Rural Electrification in Selected Sites of South Eastern Nigeria. *International Journal of Ambient Energy.* 38 (1), pp. 55-68. doi:10.1080/01430750.2015.1035799.

[38] Advisory Power Team (APT). (2015). Nigeria Power Baseline Report. Nigeria: Office of the Vice-President & Power Africa. pp. 14-15, 22 - 23 and 26 - 27.

[39] Energy Conversion. (2005). *Calculation of CO_2 emissions from fuels.* [online] available from http://people.exeter.ac.uk/TWDavies/energy_conversion.htm. [20th January, 2017]

[40] International Bank for Reconstruction and Development (2017) The State of Electricity Access Report. The World Bank Group. pp. 1 – 80

[41] The Economist Intelligence Unit (2016) Power Up: Delivering renewable energy in Africa. The Economist Group. pp. 1 – 31

[42] The Oxford Institute for Energy Studies (2018). Electrifying Africa. Oxford Energy Forum. 115, pp. 1 – 51

[43] Schwerhoff, G. and Sy, M. (2019). Developing Africa's energy mix. *Climate Policy*. 19 (1), pp. 108 – 124.

[44] Hafner, M., Tagliapietra, S., Falchetta, G. and Occhiali, G. (2019). Renewables for Energy Access and Sustainable Development in East Africa. Cham: Springer International Publishing, pp. 9 - 16.

[45] Alao, A. A. (2016). Residential and Industrial Electricity Consumption Dynamics and Economic Growth in Nigeria 1980 – 2010*. International Journal of Economy, Energy and Environment*. 2, pp. 48 - 49.

[46] Oyedepo, S. O. (2012). Energy and Sustainable Development in Nigeria: The Way Forward. *Energy, Sustainability and Society*. 2 (15), pp. 1 - 12.

[47] Ifegwu, C., Igwo-Ezikpe, M.N., Anyakora, C., Osuntoki, A., Oseni, K.A. and Alao, E.O. (2013). 1-Hydroxypyrene Levels in Blood Samples of Rats after Exposure to Generator Fumes. *Biomark Cancer*. 5, pp. 1 - 6.

[48] United Nations Fact Sheet on Climate Change (2006). Africa is particularly vulnerable to the expected impacts of global warming. United Nations Climate Change Conference, Nairobi, Kenya. pp. 1 – 2.

[49] Africa Renewal (2016). *Paris Agreement on climate change: One year later, how is Africa faring?* [online]
available from https://www.un.org/africarenewal/magazine/may-july-2017/paris-agreement-climate-change-one-year-later-how-africa-faring
[24th June, 2019]

[50] M-KOPA Solar (2019). *Our Impact* [online] available from http://solar.m-kopa.com/about/our-impact/ [24th June, 2019]

[51] Presley, K., Wesseh, J. and Boqiang, L. (2016). Can African countries efficiently build their economies on renewable energy? *Renewable and Sustainable Energy Reviews*. 54, pp. 161 – 173.

[52] Okoye, C.O. and Oranekwu-Okoye, B.C. (2018). Economic feasibility of solar PV system for rural electrification in sub-Sahara Africa. *Renewable and Sustainable Energy Reviews*. 82, pp. 2537 – 2547.

[53] Trotter, P.A., McManus, M.C. and Maconachie, R. (2017). Electricity planning and implementation in sub-Saharan Africa: A systematic review. *Renewable and Sustainable Energy Reviews*. 74, pp. 1189 – 1209.

[54] Chakamera, C. and Alagidede, P. (2018). Electricity crisis and the effect of CO_2 emissions on infrastructure-growth nexus in sub-Saharan Africa. *Renewable and Sustainable Energy Reviews*. 94, pp. 945 – 958.

[55] Ouedraogo, N.S. (2017). Africa energy future: Alternative scenarios and their implications for sustainable development strategies. *Energy Policy*.106, pp. 457 – 471.

[56] Trotter, P.A. and Abdullah, S. (2018). Re-focusing foreign involvement in sub-Saharan Africa's power sector on sustainable development. *Energy for Sustainable Development*. 44, pp. 139 – 146.

[57] Boamah, F. and Rothfub, E. (2018). From technical innovations towards social practices and socio-technical transition? Re-thinking the transition to decentralised solar PV electrification in Africa. *Energy Research and Social Science*. 42, pp. 1 – 10.

[58] Schwerhoff, G. and Sy, M. (2017). Financing renewable energy in Africa – Key challenge of the sustainable development goals. *Renewable and Sustainable Energy Reviews*. 72, pp. 393 – 401.

[59] Barasa, M., Bogdanov, D., Oyewo, A.S. and Breyer, C. (2018). A cost optimal resolution for sub-Saharan Africa powered by 100% renewables in 2030. *Renewable and Sustainable Energy Reviews*. 92, pp. 440 – 457.

[60] Bazilian, M., Nussbaumer, P., Rogner, H., Brew-Hammond, A., Foster, V., Pachauri, S., Williams, E., Howells, M., Niyongabo, P., Musaba, L., Gallachoir, B.O., Radka, M. and Kammen, D.M. (2012). Energy access scenarios to 2030 for the power sector in sub-Saharan Africa. *Utilities Policy*. 20, pp. 1 – 16.

[61] Azimoh, C.L., Klintenberg, P., Mbohwa, C. and Wallin, F. (2017). Replicability and scalability of mini-grid solution to rural electrification programs in sub-Saharan Africa. *Renewable Energy*. 106, pp. 222 – 231.

[62] Simone, T. and Bazilian, M. (2019). The role of international institutions in fostering sub-Saharan Africa's electrification. *Electricity Journal*. 32, pp. 13 – 20.

[63] Adesanya, A.A. and Schelly, C. (2019). Solar PV-diesel hybrid systems for the Nigerian private sector: An impact assessment. *Energy Policy*. 132, pp. 196 – 207.

[64] Wojuola, R.N. and Alant, B.P. (2019). Sustainable development and energy education in Nigeria. *Renewable Energy*.139, pp. 1366 – 1374.

[65] Obeng-Darko, N.A. (2019). Why Ghana will not achieve its renewable energy target for electricity. Policy, legal and regulatory implications. *Energy Policy*. 128, pp. 75 -83

[66] Adhekpukoli, E. (2018). The democratization of electricity in Nigeria. *The Electricity Journal*. 31, pp. 1 – 6.

[67] Aliyu, A.K., Modu, B. and Tan, C.W. (2018). A review of renewable energy development in Africa: A focus in South Africa, Egypt and Nigeria. *Renewable and Sustainable Energy Reviews*. 81, pp. 2502 – 2518.

[68] Azimoh, C.L., Klintenberg, P., Wallin, F. and Karlsson, B. (2015) Illuminated but not electrified: An assessment of the impact of Solar Home System on rural households in South Africa. *Applied Energy*. 155, pp. 354 – 364.

[69] Jain, S. and Jain, P.K. (2017). The rise of Renewable Energy implementation in South Africa. *Energy Procedia*. 143, pp. 721 – 726.

[70] Ateba, B.B. and Prinsloo, J.J. (2019). Strategic management for electricity supply sustainability in South Africa. *Utilities Policy*. 56, pp. 92 – 103.

[71] Moner-Girona, M., Ghanadan, R., Solano-Peralta, M., Kougias, I., Bodis, K. and Huld, T. (2016). Adaptation of Feed-in Tariff for remote mini-grids: Tanzania as an illustrative case. *Renewable and Sustainable Energy Reviews*. 53, pp. 306 – 318.

[72] Rose, A., Stoner, R. and Perez-Arriaga, I. (2016). Prospects for grid-connected solar PV in Kenya: A systems approach*. Applied Energy*.161, pp. 583 – 590.

[73] Copernicus Atmosphere Monitoring Service (2018). *CAMS radiation service: Abuja, Nigeria* [online] available from http://www.soda-pro.com/web-services/radiation/cams-radiation-service [15th August, 2018]

[74] Future Green Technology (2018). *100W Top Quality Wholesale Mono-Crystalline PV Solar Panel* [online] available from https://fget4u.en.made-in-china.com/product/TyYJcVwubWhL/China-100W-Top-Quality-Wholesale-Mono-Crystalline-PV-Solar-Panel.html [15th October, 2018]

[75] Olowosejeje, S., Leahy, P. and Morrison, A.P. (2018). Combined effects of dust accumulation and array tilt angle on the energy yield of photovoltaic systems, poster presented to The Energy Systems Conference, London, 19th – 20th June, 2018.

[76] Rolls Battery Engineering (n.d). Battery User Manual. Surrette Battery Company Limited. pp. 7, 9 and 10 – 14.

[77] HOMER Energy (2018). *Generator Lifetime* [online] available from https://www.homerenergy.com/products/pro/docs/3.11/generator_lifetime.html [20th September, 2018]

[78] Nigeria Inflation Rate (2018). *Trading Economics* [online] available from https://tradingeconomics.com/nigeria/inflation-cpi [5th December, 2018]

[79] Nigeria Interest Rate (2018). *Trading Economics* [online] available from https://tradingeconomics.com/nigeria/interest-rate [5th December, 2018]

[80] GlobalPetrolPrices (2018). *Diesel Prices* [online] available from https://www.globalpetrolprices.com/diesel_prices/ [15th December, 2018]

[81] GlobalPetrolPrices (2018). *Gasoline Prices* [online] available from https://www.globalpetrolprices.com/gasoline_prices/ [15th December, 2018]

[82] Nigerian Electricity Regulatory Commission (2018). Handbook on Application for Licences. NERC: Licensing. pp. 2 – 15.

[83] Abuja Electricity Distribution Company (2016). *Commercial – Single and 3-phase* [online] available from http://www.abujaelectricity.com/?page_id=29 [10th January, 2019]

[84] Arowolo, W, Blechinger, P, Cader, C and Perez Y. (2019). Seeking workable solutions to the electrification challenge in Nigeria: Minigrid, reverse auctions and institutional adaptation. *Energy Strategy Reviews*. 23, pp. 114 – 141.

[85] Luckow, P, Stanton, E.A, Fields, S, Biewald, B, Jackson, S, Fisher, J and Wilson, R. (2015). Carbon Dioxide Price Forecast. Synapse Energy Economics Inc. Massachusetts, USA. pp. 1 – 32.

[86] Rural Electrification Agency (2019). Highlighting the Rural Electrification Agency's Impact. REA. pp. 1 – 19.

[87] Forbes (2018) *3 Vicious Cycles: Links Among Financial, Physical And Mental Health* [online] available from https://www.forbes.com/sites/brettwhysel/2018/06/27/3-vicious-cycles/#14f69bbf540d [2nd April, 2020]

[88] The Conversation (2020) *COVID19: Nigeria should prioritise power supply to health care facilities* [online] available from http://theconversation.com/covid-19-nigeria-should-prioritise-power-supply-to-health-care-facilities-134444 [31st March, 2020]

[89] Suleiman, D.E. (2016). Mental health disorders in Nigeria: A highly neglected disease. *Annals of Nigeria Medicine*. 10, pp. 47 – 48.

[90] IRENA (2018). Global Energy Transformation: A roadmap to 2050. International Renewable Energy Agency, Abu Dhabi. pp. 1 – 73.

[91] Kapustin, N.O. and Grushevenko, D.A. (2020). Long-term electric vehicles outlook and their potential impact on electric grid. *Energy Policy*. 137, pp. 1 – 10.

[92] Colenbrander, S., Gouldson, A., Sudmant, A.H. and Papargyropoulou, E. (2015). The economic case for low-carbon development in rapidly growing developing world cities: A case of Palembang, Indonesia. *Energy Policy*. 80, pp. 24 – 35.

[93] ESMAP (2019). Mini Grids for Half a Billion People: Market Outlook and Handbook for Decision Makers. Executive Summary. Energy Sector Management Assistance Program (ESMAP) Technical Report 014/19. Washington, DC: World Bank. pp. 1 – 60.

[94] Peffley, T.B. and Pearce, J.M. (2020). The potential for grid defection of small and medium enterprises using solar photovoltaic, battery and generator hybrid systems. *Renewable Energy*. 148, pp. 193 – 204.

[95] Murugaperumal, K., Srinivasn, S. and Prasad, G.R.K.D.S. (2020). Optimum design of hybrid renewable energy system through load forecasting and different operating strategies for rural electrification. *Sustainable Energy Technologies and Assessments*. 37, pp. 1 – 16.

[96] Ali, S. and Jang, C-M. (2020). Optimum design of Hybrid Renewable Energy System for Sustainable Energy Supply to a Remote Island. Sustainability. 12 (1280), pp. 1 – 16.

[97] Veilleux, G., Potisat, T., Pezim, D., Ribback, C., Ling, J., Krysztofinski, A., Ahmed, A., Papenheim, J., Pineda, A.M., Sembian, S. and Chucherd, S. (2020). Techno-economic analysis of microgrid projects for rural electrification: A systematic approach to the redesign Koh Jik off-grid case study. *Energy for Sustainable Development*. 54, pp. 1 – 13.

[98] Babatunde, O.M., Adedoja, O.S., Babatunde, D.E. and Denwigwe, I.H. (2019). Off-grid hybrid renewable energy system for rural healthcare centres: A case study in Nigeria. *Energy Science and Engineering*. 7, pp. 676 – 693.

[99] Franco, A., Shaker, M., Kalubi, D. and Hostettler, S. (2017). A review of sustainable energy access and technologies for healthcare facilities in the Global South. *Sustainable Energy Technologies and Assessments*. 22, pp. 92 – 105.

[100] Olowosejeje, S., Leahy, P. and Morrison, A. P. (2020). A practical approach for increased electrification, lower emissions and lower energy costs in Africa. *Sustainable Futures.* 2, pp. 1 – 10.

[101] Foles, A., Fialho, L., and Collares-Pereira, M. (2020). Techno-economic evaluation of the Portuguese PV and energy storage residential applications. *Sustainable Energy Technologies and Assessments*. 39, pp. 1 – 16.

[102] Cucchiella, F., D’Adamo, I., Gastaldi, M. and Stornelli, V. (2018). Solar Photovoltaic Panels Combined with Energy Storage in a Residential Building: An Economic Analysis. *Sustainability*. 10 (3117), pp. 1 – 29.

[103] The United Nations (2020). *Sustainable Development Goals* [online] available from https://www.un.org/sustainabledevelopment/sustainable-development-goals/ [16th March, 2020]

[104] Heinrich-Böll-Stiftung (2019). Policy Research on the imposition of 10% Tariff Duties on Solar Components: Making a way for Solar in Nigeria. Heinrich-Böll-Stiftung, Abuja, Nigeria.

[105] The Conversation (2019). *Solar power could stabilise Nigeria’s electricity grid and save it money* [online] available from http://theconversation.com/solar-power-could-stabilise-nigerias-electricity-grid-and-save-it-money-117266 [24th March, 2020]

[106] Transmission Company of Nigeria (n.d). *Transmission Rehabilitation and Expansion Programme: Strategy for Rehabilitation and Expansion to Achieve Grid Stability and Reliability* [online] available from https://tcn.org.ng/repository/projectdocuments/Transmission%20Rehabilitation%20and%20Expansion%20Program%20(TREP).pdf [1st April, 2020]

[107] Rural Electrification Agency (n.d). *The Nigeria Electrification Project (NEP)* [online] available from https://rea.gov.ng/nigeria-electrification-project-nep/ [1st April, 2020]

[108] The African Development Bank (2018). *The African Development Bank and Africa Growing Together Fund to Provide US$ 200 Million in Joint Financing to support the Nigeria Electrification Project* [online] available from https://www.afdb.org/fr/news-and-events/the-african-development-bank-and-africa-growing-together-fund-to-provide-us-200-million-in-joint-financing-to-support-the-nigeria-electrification-project-18769 [1st April, 2020]

[109] The World Bank (2018). *Abstract* [online] available from https://projects.worldbank.org/en/projects-operations/project-detail/P161885?lang=en [1st April, 2020]

[110] Rural Electrification Agency (2020). *MD/CEO of REA Tours Sura Shopping Complex Independent Power Plant (IPP) powered under the Energizing Economies Initiative (EEI)* [online] available from https://rea.gov.ng/mdceo-rea-tours-sura-shopping-complex-independent-power-plant-ipp-powered-energizing-economies-initiative-eei/ [1st April, 2020]

[111] Rural Electrification Agency (2020). *MD/CEO of REA, visits University of Lagos, Energizing Education Programme (EEP) Power Plant* [online] available from https://rea.gov.ng/mdceo-rea-visits-university-lagos-energizing-education-programme-eep-power-plant/ [1st April, 2020]

[112] Tijani, S.A., Adeyemi, A.O. and Omotehinshe, O.J. (2016). Lack of Maintenance Culture in Nigeria: The Bane of National Development. *Civil and Environmental Research*. 8, pp. 23 – 30.

[113] Olowosejeje, S. (2013). Viability of Oil Refining in Nigeria: A Technical and Economic Consideration. MSc Thesis, University of Exeter, Exeter. *International Journal of Scientific and Engineering Research*. 4 (1), pp. 1 – 87.

[114] Vanguard (2020). *Nigeria's oil, gas earnings up 3% to ₦ 5.54trn* [online] available from https://www.vanguardngr.com/2020/01/nigerias-oil-gas-earnings-up-3-to-n5-54trn/ [15th April, 2020]

[115] OPEC (2019). *OPEC share of world crude oil reserves, 2018* [online] available from https://www.opec.org/opec_web/en/data_graphs/330.htm [15th April, 2020]

[116] Ministry of Petroleum Resources (2019). *Agencies* [online] available from https://petroleumresources.gov.ng/parastatals/ [15th April, 2020]

[117] Quartz (2015). Nigeria's Buhari must start his presidency facing crippling fuel scarcity and power cuts [online] available from https://www.google.com/amp/s/qz.com/411284/nigerias-buhari-won-the-fight-for-power-now-he-has-to-give-his-country-power-the-electric-kind/amp/ [15th April, 2020]

[118] Federal Ministry of Power (2020). *Welcome to the Federal Ministry of Power* [online] available from http://www.power.gov.ng [15th April, 2020]

[119] Gursch-Adam, R. and Benková, L. (2016). The impact of demographic developments in Africa on Europe. *European View*. 15, pp. 291–304.

[120] CIC News (2020). *Nigerian immigration to Canada is booming* [online] available from https://www.cicnews.com/2020/04/nigerian-immigration-to-canada-is-booming-0414172.html [22nd April, 2020]

[121] Gribble, C. (2008). Policy options for managing international student migration: the sending country's perspective. *Journal of Higher Education Policy and Management*. 30 (1), pp. 25-39.

[122] PWC (2017). *Spotlight: The Nigerian Film Industry* [online] available from https://www.pwc.com/ng/en/assets/pdf/spolight-the-nigerian-film-industry.pdf [22nd April, 2020]

[123] Inter-ministerial Committee on Renewable Energy and Energy Efficiency (2016). National Energy Efficiency Action Plans (NEEAP): 2015 – 2030. National Council on Power (NACOP), 1st edition. Federal Republic of Nigeria.

[124] Inter-ministerial Committee on Renewable Energy and Energy Efficiency (2016). National Renewable Energy Action Plans (NREAP): 2015 – 2030. National Council on Power (NACOP), 1st edition. Federal Republic of Nigeria.

[125] Inter-ministerial Committee on Renewable Energy and Energy Efficiency (2016). Sustainable Energy for All Action Agenda (SE4ALL-AA). National Council on Power (NACOP), 1st edition. Federal Republic of Nigeria.

[126] Rural Electrification Agency (2016). Rural Electrification Strategy and Implementation Plan (RESIP). Federal Ministry of Power, Works and Housing. Federal Republic of Nigeria.

[127] Nigerian Electricity Management Services Agency (2016). Inspection Report on Lower Usuma Dam 1.2MW PV System. NEMSA, Nigeria.

[128] Blue Camel Energy (2020*). Our Flagship Project: Living Off-The-Grid in Nigeria* [online] available from https://bluecamelenergy.com.ng/ [26th April, 2020]

[129] Rural Electrification Agency (2020). *REA* [online] available from https://rea.gov.ng/ [26th April, 2020]

[130] Odeleye, D.A. (2009). Repositioning Nigeria's Education for Relevance in the 21st Century. Ibadan, Nigeria, Edition: 1st edition. Chapter: 18, Publisher: College Press & Publishers Limited, pp.330 – 355.

[131] Otene, I.J.J., Murray, P. and Enongene, K.E. (2016). The Potential Reduction of Carbon Dioxide (CO_2) Emissions from Gas Flaring in Nigeria's Oil and Gas Industry through Alternative Productive Use. *Environments*. 3 (31), pp. 1 – 20.

[132] Climatelinks (2019).*Greenhouse Gas Emissions Factsheet: Nigeria* [online] available from https://www.climatelinks.org/resources/greenhouse-gas-emissions-factsheet-nigeria [27th April, 2020]

[133] Rural Electrification Agency (2017). The Nigeria Electrification Project (NEP) [online] available from https://rea.gov.ng/nigeria-electrification-project-nep/ [27th April, 2020]

[134] Power Sector Recovery Programme (2017). Fact Sheet. The Presidency, Federal Republic of Nigeria.

[135] Transmission Company of Nigeria (2017). Transmission Rehabilitation and Expansion Programme. TCN. Federal Republic of Nigeria.

[136] Emodi, N.V., Gungah, A. and Dioha, M.O. (2019). Improving Nigeria's renewable energy policy design: A case study approach. *Energy Policy*. 130, pp. 89 – 100.

[137] Bank of Industry (2018). *Economic Development through the Nigerian Informal Sector: A BOI perspective* [online] available from https://www.boi.ng/wp-content/uploads/2018/05/BOI-Working-Paper-Series-No2_Economic-Development-through-the-Nigerian-Informal-Sector-A-BOI-perspective.pdf [24th April, 2020]

[138] The Conversation (2020). *Lagos' size and slums will make stopping the spread of COVID-19 a tough task* [online] available from https://theconversation.com/lagos-size-and-slums-will-make-stopping-the-spread-of-covid-19-a-tough-task-134723 [24th April, 2020]

[139] Diemuodeke, E.O., Hamilton, S. and Addo, A. (2016). Multi-criteria assessment of hybrid renewable energy systems for Nigeria's coastline communities. *Energy, Sustainability and Society*. 6 (26), pp. 1 – 12.

[140] Avila, N., Carvallo, J. P., Shaw, B. and Kammen, D. M. (2017). The energy challenge in sub-Saharan Africa: A guide for advocates and policy makers: Part 1: Generating energy for sustainable and equitable development. Oxfam Research Backgrounder series.

[141] EY (2020). COVID19: How net-zero emissions present the power sector with an opportunity [online] available from https://www.ey.com/en_ie/power-utilities/how-net-zero-emissions-present-the-power-sector-with-an-opportunity [31st May, 2020]

[142] Förstl, M., Azuatalam, D., Chapman, A.C., Verbič, G., Jossen, A. and Hesse H. (2019). Assessment of residential battery storage systems and operation strategies considering battery aging. *International Journal of Energy Research*. 44, pp. 718 – 713.

[143] Cuesta, M.A., Castillo-Calzadilla, T. and Borges, C.E. (2020). A critical analysis on hybrid renewable energy modelling tools: An emerging opportunity to include social indicators to optimise systems in small communities. *Renewable and Sustainable Energy Reviews*. 122, pp. 1 – 13.

[144] Babatunde, O.M., Munda, J.L. and Haman, Y. (2019). Selection of a Hybrid Renewable Energy Systems for a Low-Income Household. *Sustainability*. 11 (4282), pp. 1 – 24.

[145] Agyekum, E.B. and Nutakor, C. (2020). Feasibility study and economic analysis of stand-alone hybrid energy system for southern Ghana. *Sustainable Energy Technologies and Assessments*. 39, pp. 1 – 12.

[146] Emodi, N.V., Emodi, C.C., Murthy, G.P. and Emodi, A.S.A. (2017). Energy policy for low carbon development in Nigeria: A LEAP model application. *Renewable and Sustainable Energy Reviews*. 68, pp. 247 – 261.

[147] Rasheed, R., Rizwan, A., Javed, H., Yasar, A., Tabinda, A.B., Bhatti, S.G. and Su, Y. (2020). An analytical study to predict the future of Pakistan's energy sustainability versus rest of South Asia. *Sustainable Energy Technologies and Assessments.* 39, pp. 1 – 21.

[148] Adenle, A.A. (2020). Assessment of solar energy technologies in Africa-opportunities and challenges in meeting the 2030 agenda and sustainable development goals. *Energy Policy*. 137, pp. 1 – 16.

[149] Liu, H., Azuatalam, D., Chapman, A.C. and Verbič, G. (2019). Techno-economic feasibility assessment of grid-defection. *Electrical Power and Energy Systems*. 109, pp. 403 – 412.

[150] Hittinger, E. and Siddiqui, J. (2017). The challenging economics of US residential grid defection. *Utilities Policy*. 45, pp. 27 – 35.

[151] Gorman, W., Jarvis, S. and Callaway, D. (2020). Should I Stay or Should I Go? The importance of electricity rate design for household defection from the power grid. *Applied Energy*. 262, pp. 1 – 20.

[152] Fodhil, F., Hamidat, A. and Nadjemi, O. (2019). Potential, optimisation and sensitivity analysis of photovoltaic-diesel-battery hybrid energy system for rural electrification in Algeria. *Energy*. 169, pp. 613 – 624.

[153] Oyewo, A.S., Aghahosseini, A., Ram, M. and Breyer, C. (2020). Transition towards decarbonised power systems and its socio-economic impacts in West Africa. *Renewable Energy*. 154, pp. 1092 – 1112.

[154] IEA – Nigeria (2021). *Key energy statistics, 2018* [online] available from https://www.iea.org/countries/nigeria#data-browser [2nd February, 2021]

[155] Zainal, Z. (2007). Case study as a research method. Faculty of Management and Human Resource Development. Universiti Teknologi Malaysia.

[156] Ramdas, A., Gonclaves, D.P. and Sunjka, B. (2020). Applying a Case Study Method in Systems Engineering research. *Annual INCOSE International Symposium*. 30, pp. 1 – 13.

[157] Adhabi, E. and Anozie, C.B. (2017). Literature review for the type of interview in qualitative research*. International Journal of Education*. 9 (3), pp. 1 – 13.

[158] Jones,T.L., Baxter, M.A.J. and Khanduja, V. (2013). A quick guide to survey research. *Annals of the Royal College of Surgeons, England*. 95, pp. 5 – 7.

[159] Business Research Methodology (n.d). *Survey Method* [online] available from https://research-methodology.net/research-methods/survey-method/
[17th February, 2021]

[160] Batchelor, S., Brown, E., Leary, J., Scott, N., Alsop, A. and Leach, M. (2018). Solar electric cooking in Africa: Where will the transition happen first? *Energy Research & Social Science*. 40, pp. 257 – 272.

[161] Jones, D. and Brischke, C. *Performance of Bio-based Building Materials.* Oxford, UK: Woodhead Publishing, 2017, pp. 294 – 320.

[162] RAYmaps (2013). *How to Calculate the Surface Area Required by Solar Panels* [online] available from http://www.raymaps.com/index.php/how-to-calculate-the-area-required-by-solar-panels/ [25th August, 2018].

[163] Energy Solutions (2018). Off Grid Guide – A definitive guide to powering your home or business off grid. pp. 1 – 20.

Biliography

Ewesor, P.O. *Practical electrical systems installation: Work and Practice,* 2nd edition. Benin, Nigeria: Petvirgin Partners, 2010, pp. 1 – 336.

Hahn, B.D. and Valentine, D.T. *Essential Matlab for Engineers and Scientists*, 6th edition. Oxford, UK: Academic Press, 2017, pp. 1 – 200 and 280 – 350.

Lahmeyer (International) Consultants (2005). Report on Nigeria Wind Power Mapping Projects; Federal Ministry Science Technology: Abuja, Nigeria, pp. 37–51.

Leahy, P. Lecture Notes 1 – 11. *Lectures delivered in Wind Engineering, Module Code: NE 6003*. University College Cork (UCC). 4th Oct – 5th Dec, 2016.

Louie, H. *Off-grid Electrical Systems in Developing Countries,* 1st edition. Springer International Publishing, 2018, pp. 3 – 467.

McEvoy, A., Markvart, T. and Castenar, L. *Practical Handbook of Photovoltaics: Fundamentals and Applications,* 2nd edition. Oxford, UK: Academic Press, 2012, pp. 722 – 803.

Morrison, A.P. Lecture Notes 1 – 18. *Lectures delivered in Photovoltaic Systems, Module code: NE 4008.* University College Cork (UCC). 20th Sept – 1st Dec, 2016.

PWC (2016). The power sector in Nigeria: Powering Nigeria for the Future. PricewaterhouseCoopers. July 2016, pp. 1 – 36

Solar Plaza (2018). *Africa Solar Impact Cases: Solar projects showing the life-changing capacity solar electrification* [online] available from https://africa.unlockingsolarcapital.com/home#about-gogla [18th October, 2018]

Urmee, T., Harries, D. and Holtorf, H-G. *Photovoltaics for Rural Electrification in Developing Countries: A Road Map.* Switzerland: Springer International Publishing, 2016, pp. 1 – 243.

Appendix One

Survey of commonly-occurring commercial activities in Abuja commercial centres

S/N	Commercial Centre	1	2	3	4	5
	Commercial Activity	Cyber café	Boutique	Salon	Tailoring	Grocery shop
1	Banex	✓	✓	✓	✓	✓
2	DBM	✓	✓	✓	✓	✓
3	Emab	✓	✓	✓	✓	✓
4	Mangal	✓	✓	✓	✓	✓
5	Othni	✓	✗	✗	✓	✓
6	Mcdarnells	✓	✗	✗	✗	✓
7	Sharif	✓	✓	✓	✓	✓
8	Heroes	✓	✓	✓	✓	✓
9	Olive	✓	✓	✓	✓	✓
10	GCL	✓	✓	✓	✓	✓
11	Blue	✗	✓	✗	✗	✓
12	K-City	✓	✓	✓	✓	✓
13	Israel	✓	✓	✓	✗	✗
14	Saham	✓	✓	✗	✗	✗
15	Shelter Aid	✗	✓	✗	✗	✗
16	DBM II	✓	✓	✓	✓	✓
17	Habiba	✓	✓	✓	✓	✓
18	Kenaz	✓	✗	✗	✓	✓
19	Prime	✗	✗	✗	✗	✗
20	Poly	✓	✓	✓	✓	✓
21	Iluobe	✓	✓	✗	✓	✗
22	Omega	✓	✗	✗	✗	✓
23	Fanaha	✓	✓	✗	✓	✗
24	Millenium Verdict	✓	✓	✓	✓	✓
25	Obum	✓	✓	✓	✓	✓
26	Discovery	✓	✓	✓	✓	✓
27	Premier	✗	✗	✗	✗	✗
28	Queenfem Green	✓	✓	✓	✓	✓
29	Glory Mojec	✓	✓	✓	✓	✓
30	Standard	✓	✓	✗	✓	✓
31	Sticks and Stones	✓	✓	✗	✓	✗
32	Rochas	✗	✓	✗	✗	✗
33	Nandu	✓	✓	✓	✓	✓
34	Jinifa	✓	✓	✓	✓	✓
35	Essence	✓	✓	✓	✓	✓
36	Dansaraki	✓	✓	✓	✓	✓
37	Hiltop	✓	✓	✗	✓	✗
38	AP	✓	✓	✓	✓	✓
39	Metro	✓	✓	✓	✓	✓
40	H-Medix	✗	✓	✗	✗	✓

Appendix Two

Olowos Plaza power consumption breakdown

Monday – Friday (daytime)			
Device/Equipment	Power Rating (W)	Quantity (Unit)	Total Power (W)
PC	96	8	768
Printer	337	1	337
Air Conditioners	3000	2	6000
Fan	45	10	450
Router	18	1	18
Dryer	1000	1	1000
Nail Curing Lamp	36	2	72
Clipper	20	2	40
Fridge	418	1	418
TV	31	3	93
Total Power Consumption (W) – 9196			
Hourly Energy Consumption (kWh) – 9.2			
Base load (kWh) – 0.42			
Monday – Friday (night-time)			
Device/Equipment	Power Rating (W)	Quantity (Unit)	Total Power (W)
PC	96	8	768
Printer	337	1	337
Air Conditioners	3000	1	3000
Fan	45	10	450
Router	18	1	18
Dryer	1000	2	2000
Nail Curing Lamp	36	3	108
Clipper	20	3	60
Fridge	418	1	418
TV	31	3	93
Light bulb	15	14	210
Total Power Consumption (W) – 7462			
Hourly Energy Consumption (kWh) – 7.5			

Saturday daytime			
Device/Equipment	Power Rating (W)	Quantity (Unit)	Total Power (W)
PC	96	10	960
Printer	337	2	674
AC	3000	2	6000
Fan	45	10	450
Router	18	1	18
Dryer	1000	2	2000
Nail Curing Lamp	36	3	108
Clipper	20	3	60
Fridge	418	1	418
TV	31	3	93
Total Power Consumption (W) – 10781			
Hourly Energy Consumption (kWh) – 10.8 (weekly peak load)			
Saturday night-time			
Device/Equipment	Power Rating (W)	Quantity (Unit)	Total Power (W)
PC	96	10	960
Printer	337	2	674
AC	3000	1	3000
Fan	45	10	450

Router	18	1	18
Dryer	1000	2	2000
Nail Curing Lamp	36	3	108
Clipper	20	3	60
Fridge	418	1	418
TV	31	3	93
Light bulb	15	14	210
Total Power Consumption (W) – 7991			
Hourly Energy Consumption (kWh) – 7.99			

Sunday			
Device/Equipment	Power Rating (W)	Quantity (Unit)	Total Power (W)
AC	3000	1	3000
Fan	45	4	180
Dryer	1000	1	1000
Nail Curing Lamp	36	2	72
Clipper	20	2	40
Fridge	418	1	418
TV	31	1	31
Total Power Consumption (W) – 4741			
Hourly Energy Consumption (kWh) – 4.74			

Appendix Three

Device/Equipment power rating, brand and model for Olowos Plaza

- Light Bulb – 15W 3U T2 B22 Energy Saving Light Bulb
- PC Desktop – 65W HP 260-a104na Desktop PC
- PC Monitor – 31W HP-LA 2205wg
- LaserJet Printer and Copier – 337W HP Colour LaserJetPro MFPM180n
- Fridge – 418W Blizzard Bar20 Double Door Upright Bottle Cooler
- Television – 31W JVC LT-32C461 32" LED TV – White
- Fan – 45W Premiair 16” White Oscillating Pedestal Fan - EH1796
- Nail Curing Lamp – 36W Mylee Nail MYL11
- Hair Dryer – 1000W Swing Arm Wall Mounted Salon Hood Hair Dryer
- Internet Router – 18W Draytek Vigor 2862 Series
- Barbing Clippers – 20W Kemei Turbocharged Barber Hair Clipper
- Air Conditioner – 3000W Argo AWR322HLE Split-System Air Conditioner

Appendix Four

Olowos Plaza business operation assumptions

- Some devices/equipment are specific to certain commercial outlets i.e. fridge to commercial outlet 5; nail curing lamp, dryers and clippers to commercial outlet 3; PC, printers and router to commercial outlet 1; AC to commercial outlets 1 and 3.
- Devices/Equipment consume maximum power whenever in use.
- The same device/equipment (TV, AC, Light bulb) model and/or specification is considered for those utilised in more than one commercial centre outlet.
- Daytime operation for Mondays – Saturdays are from 9am – 6pm.
- Reduced operational hours on Sundays.
- Sunday operations are daytime only, running from noon to 5pm.
- No cycling has been considered for the refrigerator (base load) and the air conditioning unit.
- Therefore, base load has to be met 24 hrs a day, every day of the week.
- Commercial outlets 1 and 3, have a larger commercial space than the other outlets due to the nature of their commercial activity.
- Commercial outlets 1 and 3 get their cooling from air conditioners, whilst the other outlets source their artificial cooling from standing fans.
- Light bulbs are never on during the daytime.
- A limited number of devices/equipment are operated in commercial outlets 1 and 3 during the daytime from Monday – Friday. This conserves energy as load demand drops.
- During Saturday daytime, load demand increases with more devices/equipment powered on to meet the increase in commercial activity.
- Weekly peak load is recorded during Saturday daytime.
- Night-time operation for Mondays – Saturdays are from 6pm – 10pm.
- No Sunday night-time operations.
- Only commercial outlets 1, 3 and 5 are open for business on Sundays.
- As night-time approaches and the weather improves, commercial outlet 3 powers off its air conditioning unit.
- Due to the nature of the devices/equipment in commercial outlet 1, the air conditioning unit is operational for its entire business hours (daytime and night-time).
- Light bulbs are always on during the night-time.
- With a weighted average daily and weekly energy demand of 108 kWh and 757 kWh respectively.
- With a yearly energy consumption of approximately 39,497 kWh, we consider Olowos Plaza a medium scale business.
- Based on Olowos Plaza’s yearly energy consumption of 39.5 MWh, commercial outlet 1 consumes the most energy at 47% of total supplied energy, outlet 3 follows with 41%, outlet 5 with 10% and outlets 2 and 4 consuming 1% respectively.

Appendix Five

Olowos Plaza power system operations design assumptions and considerations

- Olowos Plaza’s power system is designed in meeting a weekly variable load demand, with the same total load demand from Monday – Friday (117 kWh), increased demand on Saturday (134 kWh) and reduced demand on Sunday (36 kWh).
- We worked with solar irradiation data from Copernicus Atmosphere Monitoring Service (CAMS) at latitude - tilt angle (0º), specific to Abuja, Nigeria.
- Abuja is positioned at geographical coordinates: latitude - 10ºN and longitude - 8ºE.
- We worked with a single day (24 hr) solar-irradiation data based on the average daily solar irradiation for each month of the year for 2017.
- The solar-PV system sizing for the capacity range considered, was guided by working with the lowest average daily irradiation (4.45 kWh/m2/day) for the year (August), against the commercial centre’s peak load day (Saturday).
- We determined our land size (surface area) for the range of system capacities, using the equation [162]:

$$\frac{Total\ Solar-PV\ system\ capacity\ (kW)}{solar\ constant\ \left(\frac{kWh}{m^2}\right) x\ power\ conversion\ efficiency\ (dec)} \qquad (5)$$

- The surface area was verified considering the surface area per panel rating i.e. 0.69 m^2 per 100 W panel. The result would have been divided by a “factor” if the design considered a tilt angle greater than 0º.
- Nigeria experiences on average, five to six daily peak sun hours.
- The solar-PV system operates on average 10 hours a day in a week (for most of the hybrid systems’ analysed in the study).
- We assumed a system operating temperature of 35ºC.
- The systems considered for our analysis are DC-coupled systems.
- We assumed “48 V, 60 A” MPPT charge controllers would be employed in ensuring the proper operation and interaction of the solar-PV system with the battery storage system.
- We also assumed charge controllers will work as the solar-PV system regulator/protection (especially for protection against low voltage, over-current, reverse polarity, short-circuiting, overloading etc.), with fuses, circuit breakers, isolators, surge protectors, lightning arresters and a system ground, operating as the larger power systems’ protection.
- Charge controllers replacement – thrice in the integrated power systems’ lifetime (20 years).
- The battery storage system was sized for a 50% DOD capacity based on the Plaza’s Saturday commercial operations. This meant that the plaza had a varying DOD less than 50% from Monday – Friday, and also on Sunday. This resulted in a weighted weekly average DOD in the range of 34 – 41% for the integrated power systems’ battery storage capacities analysed.
- We assumed an 85% battery charging cycling efficiency, with the battery housed in a well ventilated room to prevent gaseous build-up and risk of human exposure to harmful gases (by-product of the charging process) that could be explosive and toxic.

- With the battery storage system operating on a weekly average of 10 hours a day (for most of the hybrid systems' analysed in this study), we factored in battery storage system maintenance.
- Total battery array replacement – once in the integrated power systems' lifetime. Informed by operations, battery lifetime (cycles) and referring to Rolls battery manual.
- We employed a multi-stage (fast) battery charging regime i.e. approximately two hours to get to 80% state of charge (SOC), six hours to 100% SOC.
- We also assumed there would be an equalisation charge applied periodically and as necessary.
- Battery self-discharge of 5% per month.
- Due to the system's low DOD, we did not consider system capacity degradation to have a significant effect on the battery storage system's operation during its active lifetime, considering one replacement.
- Due to the battery's charging regime, total battery array capacities and system application, the system produced energy that was excess to demand i.e. surplus energy (MWh/yr.).
- The system's surplus energy (MWh/yr.) could not be traded due to the DisCos reluctance (repeated excuse of maintaining and revamping their networks) to engage in energy trading and the immaturity of the transactive energy market in Nigeria.
- Inverter efficiency of 85% was also considered in our systems' operation design.
- We assumed 48 V inverters would be employed. We also considered power equipment/device start-up wattage in this assumption.
- Inverter replacement – once in the integrated power systems' lifetime.
- The generator system was not employed in charging the batteries towards meeting their load requirements.
- In any case, we assumed that the generator system when operational could render an equalisation charge to the battery storage system as necessary.
- The diesel generator system operated within a range of 30 – 70% load of system capacity.
- The diesel generator (DG) system, being the more resilient of the two systems (diesel and petrol generators), was deployed in meeting the higher load demand of Olowos Plaza business operations and operated for longer hours when deployed.
- For CO_2 emissions calculation, we worked with diesel fuel emitting 2.68 kg per litre consumption and petrol emitting 2.31 kg per litre consumption.
- We also worked with 9.7 kWh and 10.8 kWh in a litre of petrol and diesel fuel respectively. Referring to the generator system data sheet (efficiency) and power system loading (efficiency at "xy" load of the power system) we were able to determine the energy being delivered per litre consumption.
- In selecting a diesel generator size, we also considered the start-up wattage for the air-conditioning units.
- Petrol generator (PG) is deployed in meeting the lesser loads of Olowos Plaza business operations.

- To prevent wet-stacking and for efficiency, the generator system is not too lightly loaded and whenever deployed is operational for at least two hours.
- Petrol generator replacement – four times in the integrated power systems' lifetime.
- Maintenance of the generator system – four times a year (once every three months).

Appendix Six

Olowos Plaza power system cost considerations and assumptions

- System costs were presented in USD ($). For conversion to Nigerian naira (₦), use conversion rates of $1 – ₦ 306.35 set by the central bank of Nigeria pertinent to the period of our analysis i.e. December 2018.
- Cost quotation from an e-commerce (Future Green Tech.) online store (Made-in-China.com) put a unit of 100W$_p$ monocrystalline PV module at $33 and 100 pieces at $3300.
- Rolls Battery (12 CS 11P) unit - $986.69.
- Stephill diesel generator (SSDK20M) unit - $12,835.48.
- Neilsen petrol generator (CT1900) unit - $272.95; with a net present value applied to the generator's replacement costs as necessary.
- The balance of system components (wires, connectors, switches etc.) were assumed to be 15% of the solar-PV system's capital costs.
- The charge controller costs were assumed to be 10% of the solar-PV system's capital costs, with a net present value applied to the replacement costs as necessary.
- The inverter costs were assumed to be 20% of the solar-PV system's capital costs, with a net present value applied to the replacement costs as necessary.
- All maintenance costs (for the solar-PV, battery storage and electric power generator systems) were informed by the negotiable price of labour/services costs in Nigeria.
- Land costs were informed by contact with a land and properties agent. Kuje a suburban town in Abuja (Federal Capital Territory) was chosen due to the wider availability of project development space.
- We enquired on the lowest land size cost relative to the lowest solar-PV system capacity and thereafter scaled the cost upwards to account for all other system sizes in the capacity range we considered.
- A uniform land area was assumed for the land size calculations.
- Shipping and import duties on the solar-PV components were not considered, as well as cost of transportation, installation and re-installation of the system's component parts.

Appendix Seven

Integrated Power Systems life cycle cost analysis

IHSS

	PV System	**Diesel Generator**	**Petrol Generator**
Input			
Capital Cost ($)	57,586	12,835	273
Energy Price per kWh ($/kWh)	0.20		
Operating Power (kW)	30	15.5	2
Avg. Operating Hours/Year	7,407	666	687
Energy Cost/Year ($)	8,111		
Maintenance Cost/Year ($)	480	653	163
Other Yearly Cost ($)	-	3455	1416
Replacement times in lifetime (excludes initial installation)			
Inverter(s)	1		
Lifetime (Years)	20		
Discount Rate (%)	14		
Inflation Rate (%)	11.44		
Output			
Lifetime Cost ($)	**58,066**	**78,009**	**26,150**

IHGS 1

	PV System	**Diesel Generator**	**Petrol Generator**
Input			
Capital Cost ($)	19,420	12,835	273
Energy Price per kWh ($/kWh)	0.25		
Operating Power (kW)	10	15.5	2
Avg. Operating Hours/Year	1,064	4,202	3,494
Energy Cost/Year ($)	9,755		
Maintenance Cost/Year ($)	165	653	163
Other Yearly Cost ($)	-	7718	1649
Replacement times in lifetime (excludes initial installation)			
Inverter(s)	1		
Lifetime (Years)	**20**		
Discount Rate (%)	14		
Inflation Rate (%)	11.44		
Output			
Lifetime Cost ($)	**19,585**	**145,653**	**29,852**

IHGS 2

	PV System	Battery Storage	Diesel Generator	Petrol Generator
Input				
Capital Cost ($)	20,522	85,257	12,835.48	272.95
Energy Price per kWh ($/kWh)	0.36			
Operating Power (kW)	10	-	15.5	2
Battery Array Capacity (kWh)	-	12	-	-
Avg. Operating Hours/Year	-	3493	4,381	886
Energy Cost/Year ($)	14,269			
Maintenance Cost/Year ($)	165	681	653	163
Other Yearly Cost ($)	-	-	8,586	401
Replacement times in lifetime (excludes initial installation)				
Battery Array	1			
Charge Controller(s)	3			
Inverter(s)	1			
Lifetime (Years)	20			
Discount Rate (%)	14			
Inflation Rate (%)	11.44			
Output				
Lifetime Cost ($)	**20,687**	**96,061**	**159,414**	**10,047**

IHGS3

	PV System	Battery Storage	Diesel Generator
Input			
Capital Cost ($)	20,522	85,257	12,835.48
Energy Price per kWh ($/kWh)	0.35		
Operating Power (kW)	10	-	15.5
Battery Array Capacity (kWh)	-	12	-
Avg. Operating Hours/Year	1,043	3,493	4,224
Energy Cost/Year ($)	13,731		
Maintenance Cost/Year ($)	165	681	653
Other Yearly Cost ($)	-	-	8,488
Replacement times in lifetime (excludes initial installation)			
Battery Array	1		
Charge Controller(s)	3		
Inverter(s)	1		
Lifetime (Years)	20		
Discount Rate (%)	14		
Inflation Rate (%)	11.44		
Output			
Lifetime Cost ($)	**20,687**	**96,061**	**157,862**

IHSBS 1

	PV System	Battery Storage	Diesel Generator
Input			
Capital Cost ($)	40,786	85,257	12,835
Energy Price per kWh ($/kWh)	0.31		
Operating Power (kW)	20	-	15.5
Battery Capacity (kWh)	-	12	-
Avg. Operating Hours/Year	2,661	3,338	2,761
Energy Cost/Year ($)	12,264		
Maintenance Cost/Year ($)	325	681	653
Other Yearly Cost ($)	-	-	5,352
Replacement times in lifetime (excludes initial installation)			
Battery Array	1		
Charge Controller(s)	3		
Inverter(s)	1		
Lifetime (Years)	20		
Discount Rate (%)	14		
Inflation Rate (%)	11.44		
Output			
Lifetime Cost ($)	**41,111**	**96,061**	**108,106**

IHSBS 2

	PV System	Battery Storage	Diesel Generator
Input			
Capital Cost ($)	60,791	85,257	12,835.48
Energy Price per kWh ($/kWh)	0.30		
Operating Power (kW)	30	-	15.5
Battery Capacity (kWh)	-	12	-
Avg. Operating Hours/Year	3,370	3,493	1,897
Energy Cost/Year ($)	11,834		
Maintenance Cost/Year ($)	480	681	653
Other Yearly Cost ($)	-	-	3,539
Replacement times in lifetime (excludes initial installation)			
Battery Array	1		
Charge Controller(s)	3		
Inverter(s)	1		
Lifetime (Years)	**20**		
Discount Rate (%)	14		
Inflation Rate (%)	11.44		
Output			
Lifetime Cost ($)	**61,271**	**96,061**	**79,339**

IHSBS 3

	PV System	Battery Storage	Diesel Generator
Input			
Capital Cost ($)	80,538	85,257	12,835.48
Energy Price per kWh ($/kWh)	0.32		
Operating Power (kW)	40	-	15.5
Battery Capacity (kWh)	-	12	-
Avg. Operating Hours/Year	3,644	3,493	1,623
Energy Cost/Year ($)	12,541		
Maintenance Cost/Year ($)	630	681	653
Other Yearly Cost ($)	-	-	3,177
Replacement times in lifetime (excludes initial installation)			
Battery Array	1		
Charge Controller(s)	3		
Inverter(s)	1		
Lifetime (Years)	20		
Discount Rate (%)	14		
Inflation Rate (%)	11.44		
Output			
Lifetime Cost ($)	**81,168**	**96,061**	**73,599**

IHSBS 4

	PV System	Battery Storage	Diesel Generator
Input			
Capital Cost ($)	100,027	85,257	12,835.48
Energy Price per kWh ($/kWh)	0.33		
Operating Power (kW)	50	-	15.5
Battery Capacity (kWh)	-	12	-
Avg. Operating Hours/Year	3,683	3,493	1,584
Energy Cost/Year ($)	13,230		
Maintenance Cost/Year ($)	775	681	653
Other Yearly Cost ($)	-	-	2,807
Replacement times in lifetime (excludes initial installation)			
Battery Array	1		
Charge Controller(s)	3		
Inverter(s)	1		
Lifetime (Years)	20		
Discount Rate (%)	14		
Inflation Rate (%)	11.44		
Output			
Lifetime Cost ($)	**100,802**	**96,061**	**67,735**

IHSBS 5

	PV System	**Battery Storage**	**Diesel Generator**
Input			
Capital Cost ($)	119,258	213,143	12,835.48
Energy Price per kWh ($/kWh)	0.53		
Operating Power (kW)	60	-	15.5
Battery Capacity (kWh)	-	28	-
Avg. Operating Hours/Year	3,705	3,545	1,510
Energy Cost/Year ($)	20,990		
Maintenance Cost/Year ($)	915	1,702	653
Other Yearly Cost ($)	-	-	2,287
Replacement times in lifetime (excludes initial installation)			
Battery Array	1		
Charge Controller(s)	3		
Inverter(s)	1		
Lifetime (Years)	20		
Discount Rate (%)	14		
Inflation Rate (%)	11.44		
Output			
Lifetime Cost ($)	**120,173**	**240,145**	**59,473**

IHSBS 6

	PV System	**Battery Storage**	**Diesel Generator**
Input			
Capital Cost ($)	138,230	298,400	12,835.48
Energy Price per kWh ($/kWh)	0.66		
Operating Power (kW)	70	-	15.5
Battery Capacity (kWh)	-	42	-
Avg. Operating Hours/Year	3791	3597	1372
Energy Cost/Year ($)	26,248		
Maintenance Cost/Year ($)	1,050	2,383	653
Other Yearly Cost ($)	-	-	1,657
Replacement times in lifetime (excludes initial installation)			
Battery Array	1		
Charge Controller(s)	3		
Inverter(s)	1		
Lifetime (Years)	20		
Discount Rate (%)	14		
Inflation Rate (%)	11.44		
Output			
Lifetime Cost ($)	**139,280**	**336,207**	**49,477**

IHSBS 7

	PV System	**Battery Storage**	**Diesel Generator**
Input			
Capital Cost ($)	156,944	298,400	12,835.48
Energy Price per kWh ($/kWh)	0.69		
Max. Operating Power (kW)	80	-	15.5
Battery Capacity (kWh)	-	42	-
Avg. Operating Hours/Year	3,869	3597	1,294
Energy Cost/Year ($)	27,096		
Maintenance Cost/Year ($)	1,180	2,383	653
Other Yearly Cost ($)	-	-	1,537
Replacement times in lifetime (excludes initial installation)			
Battery Array	1		
Charge Controller(s)	3		
Inverter(s)	1		
Lifetime (Years)	20		
Discount Rate (%)	14		
Inflation Rate (%)	11.44		
Output			
Lifetime Cost ($)	**158,124**	**336,207**	**47,583**

IHSBS 8

	PV System	**Battery Storage**	**Diesel Generator**
Input			
Capital Cost ($)	175,400	298,400	12,835.48
Energy Price per kWh ($/kWh)	0.71		
Operating Power (kW)	90	-	15.5
Battery Capacity (kWh)	-	42	-
Avg. Operating Hours/Year	3,913	3,597	1,250
Energy Cost/Year ($)	27,950		
Maintenance Cost/Year ($)	1,305	2,383	653
Other Yearly Cost ($)	-	-	1,443
Replacement times in lifetime (excludes initial installation)			
Battery Array	1		
Charge Controller(s)	3		
Inverter(s)	1		
Lifetime (Years)	20		
Discount Rate (%)	14		
Inflation Rate (%)	11.44		
Output			
Lifetime Cost ($)	**176,705**	**336,207**	**46,088**

GS

	Diesel Generator	Petrol Generator
Input		
Capital Cost ($)	12,835.48	272.95
Energy Price per kWh ($/kWh)	0.24	
Operating Power (kW)	15.5	2
Avg. Operating Hours/Year	4,537	4,223
Energy Cost/Year ($)	9,574	
Maintenance Cost/Year ($)	653	163
Other Yearly Cost ($)	8,664	1,712
Lifetime (Years)	20	
Discount Rate (%)	14	
Inflation Rate (%)	11.44	
Output		
Lifetime Cost ($)	**160,636**	**30,846**

RES

	PV System	Battery Storage
Input		
Capital Cost ($)	193,598	596,799
Energy Price per kWh ($/kWh)	1.10	
Operating Power (kW)	100	-
Battery Capacity (kWh)	-	82
Avg. Operating Hours/Year	4,068	4,692
Energy Cost/Year ($)	43,372	
Maintenance Cost/Year ($)	1,425	4,766
Replacement times in lifetime (excludes initial installation)		
Battery Array	1	
Charge Controller(s)	3	
Inverter(s)	1	
Lifetime (Years)	20	
Discount Rate (%)	14	
Inflation Rate (%)	11.44	
Output		
Lifetime Cost ($)	**195,023**	**672,413**