KARADENİZ TECHNICAL UNIVERSITY
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

IMPROVING THE RELIABILITY OF NIGERIA'S ELECTRICITY GRID WITH RENEWABLE ENERGY MICROGRIDS

MASTER THESIS

Omobolaji Oluwajuwon KOYI

DECEMBER 2019
TRABZON

KARADENİZ TECHNICAL UNIVERSITY
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

IMPROVING THE RELIABILITY OF NIGERIA'S ELECTRICITY GRID WITH RENEWABLE ENERGY MICROGRIDS

Omobolaji Oluwajuwon KOYI

This thesis is accepted to give the degree of
"MASTER OF SCIENCE"
By
The Graduate School of Natural and Applied Sciences at
Karadeniz Technical University

The Date of Submission : 03 /09 /2019
The Date of Examination : 01 /11 /2019

Supervisor : Asst. Prof. Fatih Mehmet NUROĞLU

Trabzon 2019

KARADENİZ TECHNICAL UNIVERSITY
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING
Omobolaji Oluwajuwon KOYI

IMPROVING THE RELIABILITY OF NIGERIA'S ELECTRICITY GRID WITH RENEWABLE ENERGY MICROGRIDS

Has been accepted as a thesis of
MASTER OF SCIENCE
after the Examination by the Jury Assigned by the Administrative Board of the Graduate School of Natural and Applied Sciences with the Decision Number1823 **dated** 15 /10 / 2019

Approved By

Chairman	**: Asst. Prof. Dr. Fatih Mehmet Nuroğlu**	....
Member	**: Prof. Dr. Engin Özdemir**	....
Member	**: Asst. Prof. Dr. Hakan Kahveci**	....

Prof. Dr. Asim KADIOĞLU
Director of Graduate School

PREFACE

The reliability of the Nigerian electricity grid is very low, and there have been incessant power interruptions due to various reasons such as old and obsolete grid equipment, weak and radial transmission system, over-dependence on fossil fuel, and the centralized nature of the generation system. Long transmission lines are used to transmit power to areas with low or no generation, and the result is a grid with a high flow of reactive power and losses. A way of increasing reliability and reducing the losses on the system is to install power generators close to the point of use, with this, more power can be supplied to the consumers without having to urgently modify the transmission system. By adopting renewable energy microgrids, we will be able to mitigate the effects of global warming that is ravaging the planet earth.

My special thanks go to my supervisor, Asst. Prof. Dr. Fatih Mehmet Nuroğlu, for his mentorship and support throughout my master's degree period. I also want to appreciate my family and all my friends for their help and support at all times. My story will be incomplete without you.

Omobolaji O. KOYI

Trabzon 2019

DECLARATION

I declare that the research work in this thesis titled "Improving the Reliability of Nigeria's Electricity Grid with Renewable Energy Microgrids" is an authentic research work carried out by myself Omobolaji Oluwajuwon Koyi, under the supervision of Dr. Fatih Mehmet Nuroğlu. I declare that I collected all the data used for this research work myself and I carried out the necessary experiments and analyses in the relevant laboratories. The information I received from other sources are duly shown in the text and bibliography in full. I declare that I acted in accordance with scientific research and ethical rules during the study process and I accept all legal consequences. 01/11/2019

Omobolaji O. KOYI

Master Thesis

SUMMARY

IMPROVING THE RELIABILITY OF NIGERIA'S ELECTRICITY GRID WITH RENEWABLE ENERGY MICROGRIDS

Omobolaji Oluwajuwon KOYI

Karadeniz Technical University
The Graduate School of Natural and Applied Sciences
Electrical and Electronics Engineering Graduate Program
Supervisor: Dr. Öğr. Üyesi Fatih Mehmet Nuroğlu
2019, 72 Pages, 33 Pages Appendix

The power sector over the past few decades has experienced a very insignificant growth which is highly disproportionate with the population growth, thereby leaving a large population of the country's inhabitants without access to electricity. More than 40 percent of the Nigerian population does not have access to electricity, and the ones that are already connected to the grid experience excessive interruption of power supply. The power sector comprises of old and obsolete equipment and technologies which leave the grid with low reliability and efficiency. The transmission system is more radial in nature, causing the grid to have low resilience, and always experiencing collapses. The transmission system is very weak and has a very low wheeling power capability. A solution to the low wheeling power capability of the transmission system and the low efficiency of the generation system is installing distributed generators and energy storage systems close the point of use, thereby deferring the need for transmission system investments to some other times in the future. Nigeria is yet to join the countries utilizing clean and renewable sources for electricity generation. The finite nature of fossil fuels and the negative effects of their excessive combustion on our ecosystem calls for the need to embrace a cleaner and more sustainable source of energy in which wind and solar fit into appropriately.

In this report, the effects of connecting renewable energy microgrids to Nigeria's electricity grid was investigated. The grid was modeled in DigSILENT PowerFactory and different operational scenarios were created to improve both the electrification rate and the availability of electricity in a bid to improve user experience and satisfaction. Modular distributed generators and storage systems were created and connected to the appropriate positions on the grid to meet the load demands. Wind and solar radiation data were collected and used in the simulation to show the areas that can use either one or both of the renewable sources. For all the scenarios, the grid operations in conformity with the grid code requirements were observed and recommendations were made where necessary.

Key Words: Distributed generator, Energy storage system, Microgrid, PowerFactory, Reliability, Solar energy, Solar PV, Wind energy, Wind turbine.

Yüksek Lisans Tezi

ÖZET

NIJERYA ELEKTRIK ŞEBEKESI GÜVENIRLILIĞININ YENILENEBILIR ENERJI KAYNAKLI MİKRO ŞEBEKELER ILE GELIŞTIRILMESI

Omobolaji Oluwajuwon KOYI

Karadeniz Teknik Üniversitesi
Fen Bilimleri Enstitüsü
Elektrik- Elektronik Mühendisliği Anabilim Dalı
Danışman: Dr. Öğr. Üyesi Fatih Mehmet Nuroğlu
2019, 72 Sayfa, 33 Sayfa Ek

Son yıllarda enerji sektörü, nüfus artışıyla oldukça orantısız şekilde büyüme yaşayarak nüfusunun büyük bir bölümünü elektriksiz bırakmıştır. Nüfusun yüzde 40'ından fazlasının elektriğe erişimi bulunmamakta ve şebekeye bağlı olanlar ise düzenli kesintiye maruz kalmaktadırlar. Enerji sektörü, eski ekipmanlardan ve eski teknolojilerden oluştuğu için şebeke düşük güvenilirlik ve verimlilikle çalışmaktadır. Jeneratörlerin bazılarının operasyonel ömrü geçmiş ve ekipman arızası ile yedek parça eksikliğinden dolayı aksamalar yaşanmaktadır. İletim sisteminin radyal olması, şebekenin düşük esnekliğe sahip olmasına ve daima çökmelerin yaşanmasına sebep olmaktadır. İletim sistemi çok zayıf ve çok düşük iletim kapasitesine sahiptir. Bu duruma çözüm olarak, kullanım noktalarına yakın yerlerde dağıtılmış üretim sistemleri ve enerji depolama sistemleri kurulmalıdır.

Elektrik üretimi fosil yakıtlara büyük ölçüde bağımlıdır, elektrik üretim santrallerinın büyük bir kısmı doğal gazla beslenmektedir ve geri kalanlar ise buhar ya da hidroelektrik santralleridir. Fosil yakıtların sınırlı doğası ve aşırı yanmanın ekosistemimiz üzerindeki olumsuz etkileri, rüzgar ve güneş gibi daha temiz ve sürdürülebilir enerji kaynaklarının benimsenmesi ihtiyacını doğurmaktadır.

Bu tezde, yenilenebilir enerji mikro şebekelerin Nijerya'nın elektrik şebekesine bağlanmasının etkileri araştırılmıştır. Şebeke, DigSILENT PowerFactory'de modellenerek kullanıcı deneyimini ve memnuniyetini artırmak amacıyla hem elektrifikasyon oranını hem de elektriğin kullanılabilirliğini iyileştirmek için farklı operasyonel senaryolar oluşturulmuştur. Yük taleplerini karşılamak için modüler dağıtılmış üretim ve depolama sistemleri oluşturulmuş ve şebekedeki uygun noktalara bağlanmıştır. Rüzgar ve güneş ışınım verileri simulasyonda kullanılarak yenilenebilir kaynaklardan biri veya her ikisini de kullanabilecek alanlar belirlenmeye çalışılmıştır. Tüm senaryolar için, şebekeye uygunluk gözlenmiş ve gerektiğinde önerilerde bulunulmuştur.

Anahtar Kelimeler: Dağıtılmış Üretim*s*, Enerji depolama sistemi, Mikro şebeke, Powerfactory, Güvenilirlik, Güneş enerjisi, PV sistem, Rüzgar enerjisi, Rüzgar türbünü.

ACKNOWLEDGMENT

I will like to appreciate my family for their support throughout the course of my education, I am really grateful for all their sacrifices and commitments without which I would not have come this far.

I will also like to appreciate my supervisor, Asst. Prof. Dr. Fatih Mehmet NUROĞLU. I cannot express enough with words how grateful and privileged I feel to have worked under his supervision. I believe without a shred of doubt that I am a better person technically now than before I started to work with him. You really have been so listening and encouraging, always willing to go out of your ways to ensure that your students have the best experience. I will always remember the periods that I worked under you.

My acknowledgment will not be complete without mentioning the names of some of the people that added some spices to my experience here in Trabzon. Jamiu Oluwaseun Ojeleye, it has been really nice meeting you, and I so much appreciate you for your dedication and commitments to your academics, I wish you all the very best in all your life’s endeavors. Abdulrahman Musa Muhammed, you also have been wonderful, and our experiences will resonate with me for a long time. Ridwan Bello, it has been nice to also have you on board, I also wish you the very best. To all my friends whose names I didn’t mention, you are all very important to me and have in a way or another helped shape my experiences during this journey, you all are dearly appreciated. I will also like to thank Hatice Okumuş for all the help she rendered during the writing of this thesis. And lastly, to my very good friend, Aron Tesfalem, I appreciate all your help during the submission of this thesis.

It will amount to a gargantuan and prodigiously indecorous deportment to halt or culminate the operation of my thankfulness without interjecting the nomenclature of my very benevolent and altruistic benefactor, Yurtdışı Türkler ve Akraba Topluluklar Başkanlığı, (YTB), for their generosity and undiluted amiability, I will forever be grateful.

Lastly, I will like to show my profound appreciation to DigSILENT GmbH for providing me with a licensed copy of the PowerFactory 2018 SP5 software for free for my research study.

TABLE OF CONTENTS

Page No:

LIST OF FIGURES

Page No:

LIST OF TABLES

Page No:

ABBREVIATIONS

AC:	Alternating Current
BESS:	Battery Energy Storage System
CC:	Central Controller
DC:	Double Circuit
dc:	Direct Current
DER:	Distributed Energy Resource
DFIG:	Doubly-Fed Induction Generator
DG:	Distributed Generator
DHI:	Diffuse Horizontal Irradiation
DisCo:	Distribution Company
DNI:	Direct Natural Irradiation
DoD:	Depth of Discharge
ESS:	Energy Storage System
FA:	Forced Air
FOW:	Forced Oil-Water
GenCo:	Generation Company
GHG:	Greenhouse Gas
GHI:	Global Horizontal Irradiation
G.S.:	Generation Station
GSA:	Global Solar Atlas
GWA:	Global Wind Atlas
HAWT:	Horizontal Axis Wind Turbine
LV:	Low Voltage

MC:	Microsource Controller
NDPHC:	Niger Delta Power Holding Company
NEPA:	National Electric Power Authority
NERC:	Nigeria Electricity Regulatory Commission
NIPP:	National Integrated Power Projects
NPC:	National Population Commission
NSO:	Nigeria Electric System Operator
OA:	Oil Air
ODAF:	Oil Directed Air Forced
ODWF:	Oil Directed Water Forced
OECD:	Organization for Economic Cooperation and Development
OFAF:	Oil Forced Air Forced
OFW:	Forced Oil-Water
OFWF:	Oil Forced Water Forced
OHL:	Overhead Line
ONAF:	Oil Natural Air Forced
ONAN:	Oil Natural Air Natural
PCC:	Point of Common Coupling
PF:	Power Factor
PV:	Photovoltaic
P.S.:	Power Station
PwC:	PricewaterhouseCoopers
REMP:	Renewable Energy Master Plan
RESIP:	Rural Electrification Strategy and Implementation Plan

SC:	Single Circuit
TCN:	Transmission Company of Nigeria
T.S.:	Transmission Substation
VAWT:	Vertical Axis Wind Turbine
WRA:	Wind Resource Assessment

1. INTRODUCTION

1.1. Background

Over the past few decades, the Nigerian electricity system has been highly inadequate in discharging its duties of making electricity available to the Nigerian populace. The electricity infrastructure of the country has experienced little to no improvements for a long period of time, and this has resulted in shortages of electricity supply to customers. Both the generation and transmission systems are overdue for renovation and overhauling. The decay in the electricity infrastructure is such that the electricity system cannot provide constant and adequate electricity to half of the population of Nigeria at any given time. According to (World Bank, n.d.), the electrification rate of Nigeria was 52.5% in 2015 and 59.3% in 2016. With an estimated population of about 195 million people in 2019, it suffices to say that about 80 million Nigerians do not have access to the national grid.

All around the world, the advocacy for green and sustainable energy sources is on the rise, and a contributory factor to such clamoring is the glaring effects of global warming on planet earth. There have been notices of sea level rises, unstable weather patterns, flood, and temperature rises, among other effects of global warming. Global warming is principally caused by the continuous combustion of fossil fuels, which among its end products are the greenhouse gases that are released into the atmosphere. Nigeria in a way is highly culpable in the practice of releasing greenhouse gases into the atmosphere, as most of the power plants use thermal generators that run on natural gas. Also, the practice of flaring gases is very common at the gas refineries, and all these contribute to global warming.

Nigeria’s electricity infrastructure is characterized by a high level of generation and transmission deficits, poor reliability due to incessant power outages, failures, load shedding, faults, and aging equipment in the network (Airoboman, Ogujor, and Okakwu, 2017). The country has one of the lowest electricity per capita in the world, given by (World Bank, n.d.) as

144.5 kWh in 2014, lesser than smaller African countries such as Ghana and Togo with 355 kWh and 153 kWh respectively. Nigeria is the most populous country in Africa, its population is constantly increasing, but an equal level of increase is not reflected in the power sector, and this has resulted in the power system infrastructure been very inefficient in meeting the needs of the customers. Nigeria has an installed generation capacity of about 12 GW, and its available generation capacity is barely above 5 GW for its enormous population. The electricity system is also characterized by a high level of transmission and distribution losses which contribute to the unreliability of the entire power system. The transmission system according to (Transmission Company of Nigeria [TCN], n.d.) is said to have a capacity of 8100 MW. The transmission system capacity is expected to be upgraded to allow for proper and efficient wheeling of power across the network. A contributory factor to the low generation capacity is poor maintenance culture of the GenCos, which leaves a lot of the generation units with various faults that prevent them from being put in production. Other factors that affect the generation capacity of the gas power plants are gas constraints and sabotage of the gas pipelines by agitating youths.

Renewable energy based microgrids are expected to alleviate the issues prominent with the Nigerian power sector, such as transmission and generation deficits, and reliability problems while also helping to mitigate the effects of climate change, and at the same time increasing the sustainability of the entire power generation process. Also, renewable energy microgrids can help in deferring investments in the power transmission sector, as the distributed generators will be connected close to the load, which means that a large proportion of the generated power is utilized around the site of production. Nigeria has potentials for solar, wind and run-of-the-river hydro among other renewable primary energy sources. The northern part of Nigeria has a higher altitude than the western and the southern part of the country, which by implication translates to higher wind and solar potentials that are commercially viable for electricity generation. The northern part of Nigeria on the average has a low electrification rate because of the sparse nature of its population, which means that a lot of communities are far from the national grid and are unable to be provided electricity due to the economic and reliability implications of constructing long transmission lines. With microgrids, both the reliability and electrification rates can be improved.

A growing economy such as that of Nigeria needs adequate energy for its further developments. Energy availability and economic developments are directly proportional and inseparable, and for Nigeria to meet its economic and environmental goals, concise efforts must be made to provide the citizenry with both reliable and sustainable energy that does not impact the people's health and the environment adversely.

The content of this thesis is divided into five chapters, with discussions that encompass the current state of the electricity infrastructure, the renewable energy potentials of the country, ways and means of mitigating the current electricity deficiencies, and how connecting microgrids to the weak points of the grid will help to improve the reliability and operational efficiency of the entire power system. In chapter one, the general overview of the problems currently facing Nigeria's electricity infrastructure is given, the aim and the objectives of this thesis, as well as its scope, are discussed. A review of some of the works of different authors that have in the past done researches on the Nigerian power system is given in chapter two. Also, the present states and operational capabilities of the generation, transmission, and distribution systems are reviewed. In chapter three, the renewable energy potentials of Nigeria is discussed with a particular focus on wind, solar, and pumped hydroelectric energy resources. Battery energy storage system and renewable energy trends around the world are also discussed. In chapter four, operational scenarios are formulated to observe how the grid will perform under load increments, and with microgrids connections at the grid's weakest points. In chapter five, recommendations are given on what needs to be done to achieve a more reliable and efficient power system.

1.2. Problem Statement

The Nigerian electricity grid has for a long time been plagued with incessant power interruptions, high unreliability, poor power quality, and low electrification rate. Presently, fossil fuel has a higher share of the primary energy sources, with hydropower only providing a small percentage of the entire electricity production of the country.

The need to improve the electrification rate of the country by providing electricity to the rural residents who are located far away from the national grid, and at the same time improving reliability and security by introducing renewable energy based microgrids with energy storage systems, which can securely operate in grid-connected and islanded modes to improve consumer satisfaction while also mitigating the release of greenhouse gases into the atmosphere from excessive fossil fuel combustion is the motivation for carrying out this research work.

1.3. Aim and Objectives

This research work aims at investigating the ability of renewable energy based microgrids to improve the reliability, security, and electricity availability of the Nigerian national grid, which at the moment, almost entirely utilizes fossil fuel as the primary energy source. The outcome of this research is aimed at improving Nigeria's electricity consumers experience by improving the reliability of the electricity grid, while also improving power quality. The aims of this research work will be achieved through the following objectives: -

1. To simulate the 330 kV and 132 kV circuits of the national grid with all the power generations and load demands adequately represented.
2. To perform load flow analysis on the grid so as to be able to identify the critical buses with deviations from the statutory voltage and frequency limits.
3. To obtain the optimal sizes and locations of the distributed generators and energy storage systems.
4. To investigate the grid-connected, and islanded modes of operation of the microgrids, and their effects on the national grid.

1.4. The Scope of the Study

This research work is limited to the detailed simulation of the Nigerian electricity grid and its operations at the time of concluding this study in March, 2019, obtaining the optimal positions for microgrid installations for reliability improvements, sizing the microgrids to obtain 75 percent and 100 percent electrification rates and also increasing electricity availability from 15 to 24 hours a day while observing the ability of the grid components to withstand the effected changes in the load and generation. Subjecting this research work to conditions outside the scope of this study may result in outcomes for which the author of this report may not be held liable.

2. LITERATURE REVIEW

2.1. An Overview of Nigeria's Electricity System

Electricity in Nigeria is characterized by inadequacies in supply, incessant power interruptions, poor power quality, and very low reliability and security. With the present wave of renewable energy adoption around the world to achieve a greener means of generating electricity for a more sustainable society, and to reduce the rate at which greenhouse gases are released into the atmosphere, there is no better time than now for Nigeria to also be a part of this movement. Adding renewable energy to Nigeria's energy mix will go a long way in mitigating the inadequacies and shortages in electricity supply to meet the load demands. Some of the contributory factors to the low efficiency of Nigeria's electricity infrastructure are old age of some of the generators, radial nature of the transmission system, and over-dependence on fossil fuels which at times are short in supply, thereby reducing the generating capacities of the generation stations. Also, sabotage of the gas pipelines by agitating youths is a major concern when it comes to the adequate supply of natural gas to the gas power plants, and this substantially affects the electric energy production capacity of the entire country, as most of the power plants are gas-fired. The radial nature of the grid contributes immensely to its poor power quality. The resilience of the grid is low, and this affects its ability to easily recover from faults. Some of the factors that contribute to frequent outages in Nigeria are transmission lines and transformer overload, poor quality of supply, and insufficient reliability of supply (Fichtner, 2017). The reactive power on the system is high, for which reason the transformers and conductors are usually overloaded and unable to wheel as much active power as they could have been able to if the reactive power on the system was better compensated. Presently in Nigeria, the load demand is very much more than the generation capacity of the country, which necessitates incessant power interruptions and load rejections. To sufficiently meet the ever-increasing load demand, adequate efforts must be made in installing more generation stations with sustainable primary energy sources, and also strengthening the transmission system to increase the resilience of the entire electricity grid. A number of grid expansion projects are currently being undertaken by TCN, aimed at strengthening the transmission system to enable it to conveniently serve a load of about 10 GW by 2020. The projects include the construction of new transmission lines, reconditioning of some already existing transmission networks, and the construction of some new transmission substations.

There are about 28 power stations in Nigeria, with most of them being open cycle gas turbine power plants. There are three hydroelectric power stations and about two steam power stations. The share of natural gas in the primary energy mix shows how overly dependent Nigeria's electricity infrastructure is on fossil fuels. Of the total installed generator capacity, 69% is gas power plants, 17% is steam power plants, and 14% is hydroelectric plants as shown in Fig. 1.

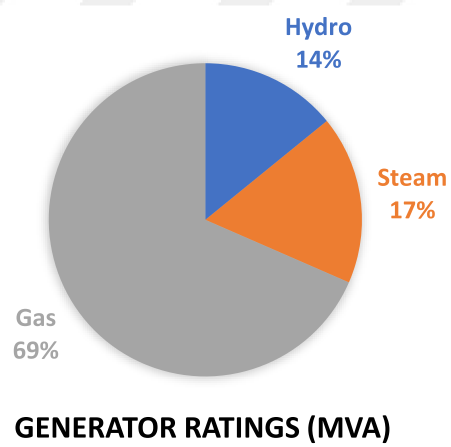


Fig. 1. Installed generation capacity

As stated in the daily operational report of 4th February 2019 provided by the Transmission Company of Nigeria, installed generation capacity, generation capacity, and transmission wheeling capacity are 12910.40 MW, 7652.6 MW, and 8100 MW respectively. The highest ever attained generation at the time of writing this report is 5375 MW, and it was obtained on 7th February 2019. It can be observed that the available generation capacity is only 59.27% of the total installed capacity. The low capacity factor is due to various reasons, among which are sabotage of gas pipelines, low efficiency of power plants due to old age, and poor maintenance culture that always leaves most of the power stations with faulty equipment, and as such, inhibit the smooth generation of electricity for consumer satisfaction. Some of the generation stations have been operational for more than 30 years, thereby immensely impacting on their abilities to function reliably and efficiently. Several of the power generators have efficiencies of less than 30% (Fichtner, 2017).

The amount of electric energy that is produced in Nigeria daily is grossly inadequate for its large population. Generation capacity of less than 5 GW for a population estimated to be about 195 million people is highly inadequate. According to the National Population Commission (NPC), in 2014, the average electrification rate in Nigeria was about 55.5%, meaning that about 80 million Nigerians do not have access to the national grid. A lot of changes have not occurred in the power sector from the time when the report was given until now. Figure 2 below shows the electrification rate for each state in Nigeria in 2014.

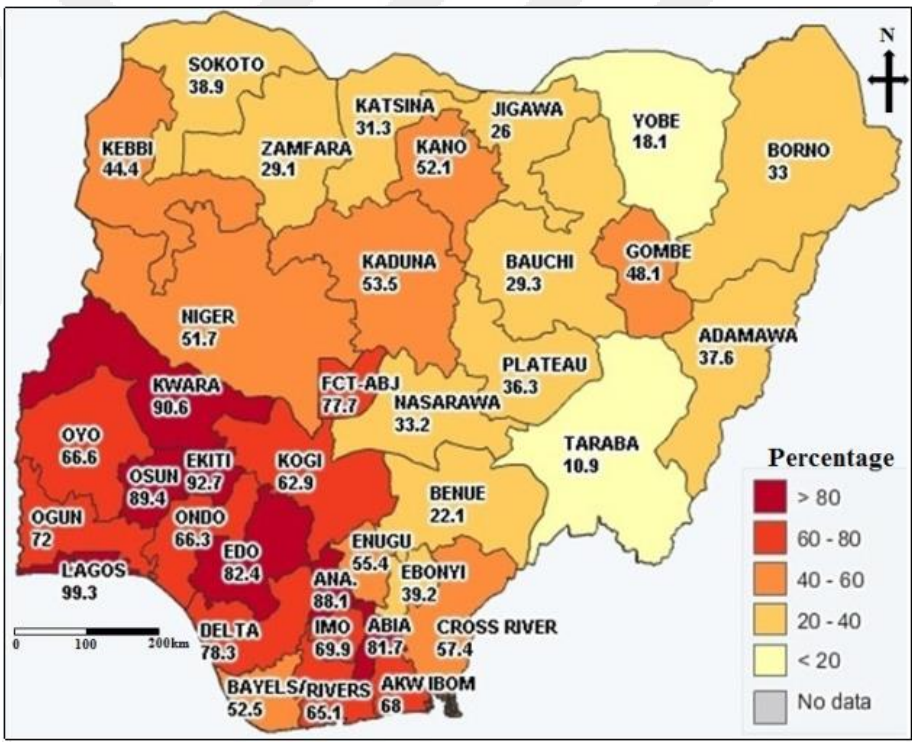


Fig. 2. Nigeria's electrification rate in 2014 (source: World Bank, 2018)

The dispersed nature of the loads in some parts of the country is a contributory factor to the low rate of access to the grid. Especially in the northern part of the country, a lot of the loads are far away from the national grid, prompting the need to construct long transmission lines, which at times might not be economical, considering the population of the customers to be serviced and the huge investments involved. As highlighted by (Sambo, 2009), electricity access is expected to rise to 75% by 2025. The north-central and the north-eastern parts of Nigeria are characterized by a total absence of generation stations, while the load demand is mainly in the south and southwest. The need to supply the loads in these areas necessitates the construction of long 330 kV transmission lines, which are majorly radial, thereby causing voltage regulatory problems due to excessive reactive power flowing through these lines (Fichtner, 2017). Figure 3 gives an idea of the locations of the power plants.

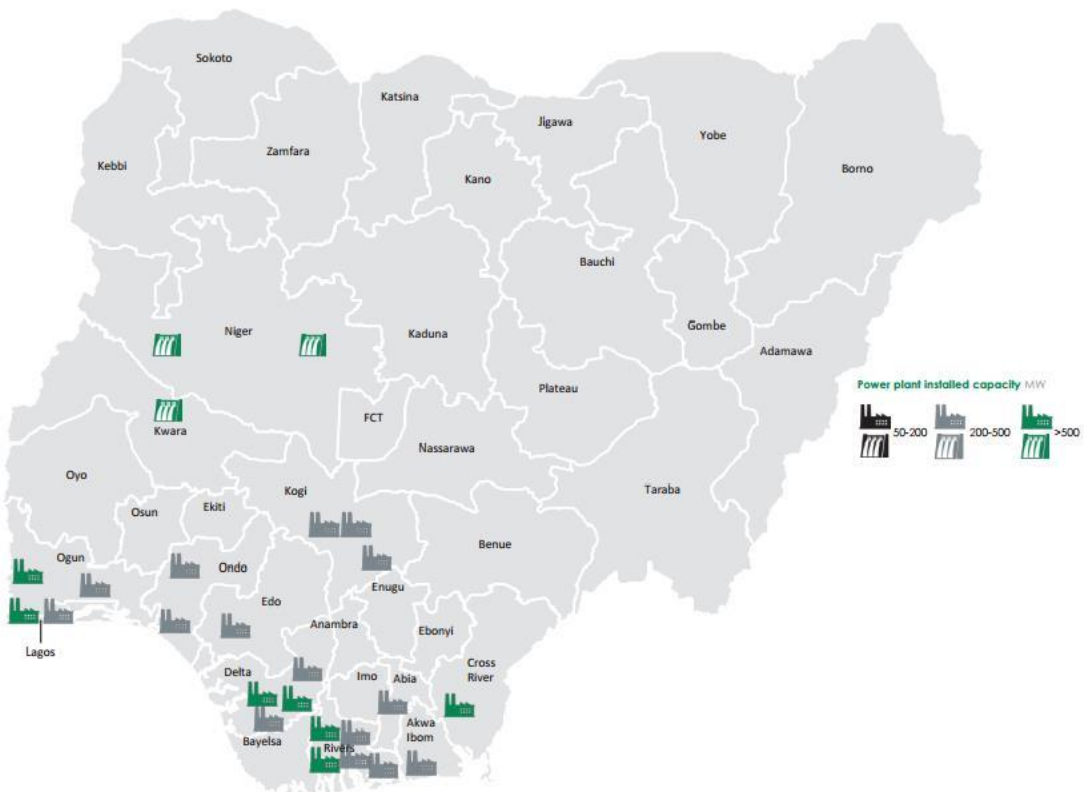


Fig. 3. Power plant locations (source: Africa-EU Renewable Energy Cooperation Programme [RECP], n.d.)

The power stations are located in the south-east, south-west, and north-west of Nigeria. These locations are chosen to achieve close proximity to the primary energy sources. The power stations in the south-eastern part of Nigeria are majorly thermal power stations, and they are close to the source of natural gas. The hydroelectric power stations in the north-western part of the country are operated by damming the River Niger. Although the north-central and the north-eastern parts of Nigeria do not have any form of generation due to lack of natural gas deposits, they are rich in solar radiation and wind speed that can be utilized for electricity generation. Harnessing the renewable energy resources in the north-central and north-eastern parts of Nigeria for electricity generation will go a long way in improving power quality, voltage stability, and also reduce the losses in these regions due to long transmission lines. The installation of renewable energy microgrids to meet the load demands will help in transmission system investment deferral and overall grid stability.

To understand the generation capability of the grid, and the closeness of its operational parameters to the statutory grid ratings, data containing the peak and off-peak generations, energy, voltage, and frequency of the grid for September 2018 is presented in Table 1 below.

Table 1. September 2018 Grid Data (source: TCN, n.d.)

Date	**Peak Gen. (MW)**	**Off-Peak Gen. (MW)**	**Energy Generated (MWh)**	**Avg. Energy Generated (MWh/h)**	**Highest Freq. (pu)**	**Lowest Freq. (pu)**	**Highest Voltage (pu)**	**Lowest Voltage (pu)**
01-09-18	4489.3	2880.3	82019.99	3417.50	1.02	1.00	1.06	0.90
02-09-18	4420.1	2760.9	82970.2	3457.09	1.01	1.00	1.06	0.91
03-09-18	4656.6	2670.8	88130.12	3672.09	1.01	1.00	1.06	0.91
04-09-18	3742.3	81	71035.12	2959.80	1.02	0.95	1.07	0.85
05-09-18	4122.1	2921.6	86721.48	3613.40	1.02	1.00	1.06	0.85
06-09-18	4316.1	2897.5	82453.69	3435.57	1.02	0.99	1.08	0.91
07-09-18	4498.1	2627.6	82915.82	3454.83	1.02	0.99	1.08	0.91
08-09-18	4627.9	2887.6	84468.1	3519.50	1.02	1.00	1.08	0.91
09-09-18	4013.7	2743.6	81301.65	3387.57	1.02	1.00	1.06	0.91
10-09-18	3966.6	2498.8	80339.65	3347.49	1.02	1.00	1.08	1.00
11-09-18	4156.1	2453.1	83937.62	3497.40	1.02	0.98	1.08	0.91
12-09-18	4598.2	3010.3	89826.4	3742.77	1.02	1.00	1.08	0.91
13-09-18	4631.9	2875.5	88436.69	3684.86	1.02	1.00	1.09	0.91
14-09-18	4576	3028.7	91036.57	3793.19	1.02	1.00	1.07	0.91
15-09-18	4515.9	3397.6	90655.03	3777.29	1.01	1.00	1.09	0.91
16-09-18	4034.5	3040.7	83316.34	3471.51	1.02	1.00	1.07	0.91
17-09-18	4831.5	2790.1	88314.25	3679.76	1.02	1.00	1.08	0.85
18-09-18	4570.4	2871.8	85689.09	3570.38	1.02	0.99	1.09	0.91

Date	Peak Gen. (MW)	Off-Peak Gen. (MW)	Energy Generated (MWh)	Avg. Energy Generated (MWh/h)	Highest Freq. (pu)	Lowest Freq. (pu)	Highest Voltage (pu)	Lowest Voltage (pu)
19-09-18	5052.6	3338.3	93683.78	3903.49	1.02	0.99	1.06	0.85
20-09-18	4194.5	168	75387.35	3141.14	1.02	0.98	1.07	0.78
21-09-18	4405.4	3224.4	91155.1	3798.13	1.02	1.00	1.07	0.88
22-09-18	4452.1	3041	84735.26	3530.64	1.02	1.00	1.13	0.91
23-09-18	4198.1	2740.1	81272.35	3386.35	1.02	1.00	1.09	0.91
24-09-18	4417	2851.2	85381.65	3557.57	1.02	1.00	1.09	0.91
25-09-18	4282	2952.6	85485.33	3561.89	1.02	1.00	1.07	0.91
26-09-18	4854.8	2868.5	91077.13	3794.88	1.01	1.00	1.07	0.90
27-09-18	4607	3301.7	90652.72	3777.20	1.01	1.00	1.07	0.91
28-09-18	4574.5	3131.6	87343.34	3639.31	1.02	1.00	1.07	0.91
29-09-18	4708.2	3125	89470.39	3727.93	1.02	1.00	1.06	0.91
30-09-18	4376.9	3225.4	90210.39	3758.77	1.02	1.00	1.07	0.91

From Table 1, a summary of the national grid performance can be seen. The highest peak generation for the month of September 2018 occurred on the 19th with a value of 5052.6 MW, and the lowest peak generation occurred on the 4th with a value of 3742.3 MW. The lowest off-peak generation was 81 MW, which is exceptionally small, and was as a result of grid collapse that left only Jebba hydroelectric power station in operation. Also, the highest average energy generated per hour was 3903.49 MWh/h. Some of the reasons for the low generation capacity are natural gas pipeline vandalization, water, and natural gas constraints, faulty generator components, poor maintenance culture, old and obsolete equipment, with transformer and transmission lines overloading. In power generation, technology limitations can be significant, as power plants typically have a wide range of capacity utilization rates depending on the technology used, as well as the age and condition of the infrastructure (PricewaterhouseCoopers [PwC], 2016). The Nigerian transmission network is very week due to the aging network and a few routes available to evacuate the generated power (Akpojedje, Onogbotsere, Mormah, and Onogbotsere, 2016). The nominal frequency of the grid is 50 Hz. The National Control Centre (NCC) is responsible for controlling the grid frequency within a narrow operating band of ± 0.5% from 50 Hz (49.75 – 50.25 Hz), but under system stress, the frequency on the power system could experience variations within the limits of 50 Hz ± 2.5% (48.75 – 51.25 Hz) (Nigeria Electricity Regulatory Commission [NERC], 2018). As highlighted in the Grid Code for the Nigeria Electric Supply Industry (NESI), the permissible voltage levels on the grid are shown in Table 2.

Table 2. Grid Voltage Ranges (source: NERC, 2018)

Voltage Level	**Minimum Voltage kV (pu)**	**Maximum Voltage kV (pu)**
330 kV	280.5 (0.85)	346.5 (1.05)
132 kV	112.2 (0.85)	145.2 (1.10)
66 kV	62.04 (0.94)	69.96 (1.06)
33 kV	31.02 (0.94)	34.98 (1.06)
11 kV	10.45 (0.95)	11.55 (1.05)

Under system stress or following system faults, the voltage can be expected to deviate outside the above limits by a further ± 5% (excluding transient and sub-transient disturbances) (NERC, 2018).

The national grid has suffered some collapses over the years. An up to date record of the number of both partial and total collapses that have occurred on the grid over the years can be found in TCN’s daily operational reports. The grid collapses are as a result of the lack of synchronization between the grid generators, which could most likely have resulted from generation and load demand mismatch. For a seamless grid operation, it is necessary to ensure that the generation capacity can meet both the load demand and grid losses. Failure of the total generation to meet load demand and grid losses will result in generators losing synchronization, and grid instability might result. Figure 4 shows the total number of grid collapses that occurred between 2010 and January 2019.

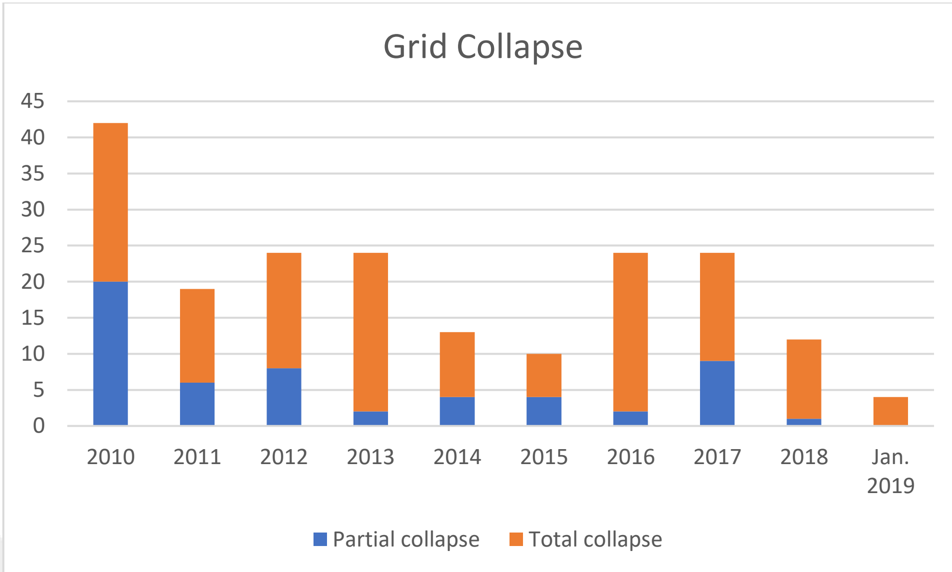


Fig. 4. Partial and total grid collapse (source: TCN, n.d.)

There were 22 total collapses and 20 partial collapses in 2010 alone. Figure 4 shows the level of fragility of Nigeria's electricity grid, and the need for urgent action to strengthen both the transmission and generation systems to make the grid more stable, resilient and reliable. 140 total grid collapses, and 60 partial grid collapses occurred between 2010 and January 2019. Strengthening the grid will require the decentralization of the generation system by installing distributed generators at different parts of the grid where additional generation capacities are needed to provide the required active power to improve the stability of the grid as well as the power quality. The transmission system can be improved by creating alternative paths within the grid for current flow, thereby increasing the resilience of the grid and also enhancing its stability. The summary of the nominal ratings of the grid components is presented in Table 3.

Table 3. Grid Components Ratings (Nation Integrated Power Projects [NIPP], 2007)

Grid Component	Rating
Transmission voltage	330 kV
Sub-transmission voltages	33 kV, 132 kV
Primary distribution feeder voltages	11 kV, 33 kV
Secondary distribution feeder voltage	415 V (three-phase)
	230 V (single-phase)
Power transformer voltage ratings	330/132/33 kV
	330/132/13.8 kV
	132/33/11 kV
	132/33 kV
	132/11 kV
Power transformer power ratings	162 MVA, 150 MVA, 90 MVA, 60 MVA, 45 MVA, 30 MVA
Circuit Breaker current ratings	16 kA, 17 kA, 20 kA, 30 kA, 31.5 kA, 40 kA, 50 kA
Transmission lines loading limits	85% of thermal rating (under normal operating condition)
	100% of thermal rating (under emergency operating condition)
Generator terminal voltages	10.5 kV, 11.5 kV, 15 kV, 15.65 kV, 15.75 kV, 16 kV
Generator loading limits	± 5% of nameplate rating
Transformer loading limit	Not more than 85% of nameplate rating

In Table 3, the grid transformers' voltage and power ratings, as well as circuit breaker ratings, can be seen. Also, the loading limits of the generators, transformers, and transmission lines are presented.

2.2. Related Works

A lot of works have been done on the Nigerian electricity system, and the evidence can be seen in the number of research reports that are available in the literature. Studies have been carried out by different authors on different aspects of the grid operations such as reliability improvement, contingency analysis, load forecasting, and grid stability among others. Among the past analyses done on the grid are (Fichtner, 2017) and (NIPP, 2007) works. From both authors, detailed information about all the grid components were presented, and comprehensive analyses were carried out to determine the grid functioning capabilities in different operational scenarios. Recommendations were made by both authors on how to improve the grid for optimal operational capabilities. Integration and evacuation study was carried out by (NIPP, 2007) in collaboration with PHCN to observe and evaluate the strength of Nigeria's electricity infrastructure in evacuating, wheeling, and delivering the generated power to the load centers and bulk load consumers of electricity by the existing and newly proposed power generation plants. For the seamless operation of the electricity infrastructure, reinforcement and expansion of the existing facilities (i.e., transmission lines, substations, and other associated equipment), and the construction of new ones was proposed. The authors suggested that a database for storing up-to-date data for studies and planning purposes should be provided to ensure that subsequent studies are based on the same set of data to enable credible comparisons of the results of the studies.

A study was carried out by Fichtner (2017) in collaboration with TCN to develop a power system master plan covering the periods between 2020 and 2037. The study covered different aspects of the grid operations such as load demand forecast, projection of existing generation capacity availability, future generation candidate considerations, generation optimization, transmission system analysis, power system analysis to study the transmission system operational capability, financial analysis, and environmental impact scoping. A comprehensive grid simulation was done using the data provided by TCN. Load forecast spanning the periods between 2016 and 2035 was done while considering the load demands of the individual DisCos. Different generation, transmission, and load demand scenarios were created to understand how the grid would perform under such conditions. Recommendations were made by the author on the required actions to be taken to optimize the operations of the national grid.

A study of the state of the power infrastructure and electricity in Nigeria, and the effects on the economy of the country, and also the welfare of the Nigerian populace was done by (Nwokoye, Dimnwobi, Ekesiobi, and Obegolu, 2017). The authors pointed out the deplorable state of Nigeria's electricity system, and the need for urgent and concerted efforts by both the government and power industry stakeholders, to adequately revamp and strengthen the power system for economic growth benefits, and for the improvement of the standard of living of the people. The authors listed the problems of Nigeria's electricity system as generation deficit, weak transmission and distribution infrastructures, poor utility performance, and a long period of investment and maintenance neglect. It was concluded that for improved operation of Nigeria's power system, the government must enact policies that allow power sector enterprises to thrive, ensure proper maintenance of the transmission and distribution networks, with adequate measures to protect the grid components from vandalism. Also, the investment in human capacity development by regularly training the staff members and engineers in the electricity sector, to ensure excellent service delivery is very important.

A review of the electricity transmission issues in Nigeria, and the challenges of rural electrification were done by (Akpojedje et al., 2016). The authors attributed the inefficiencies in the transmission of electricity in Nigeria to overloaded transmission lines, obsolete substation equipment, and lack of redundancy in the transmission lines configurations as a result of the highly redial nature of the transmission system. Adding more loops in the transmission system and the introduction of renewable energy-based microgrids to mitigate the reliability challenges of Nigeria's electric power system was recommended.

The analysis of Nigeria's electricity demand forecast from 2013 to 2030 was done by (Ezennaya, Isaac, Okolie, and Ezeanyim, 2014) by performing time series analysis using the data from past load demands. The study employed the stochastic/probabilistic extrapolation forecasting method which is based on the time series analysis of past demand curve using a straight-line graph. The authors highlighted the benefits of proper load forecasting in balancing the power generation and load distribution requirements of the power system, thereby mitigating the system failures to guarantee a higher power quality and system reliability.

Ibrahim, Mukhtar, and Gani (2017) discussed the relationship between electricity consumption, manufacturing output, and financial development in Nigeria over the period of

1981 to 2015. The authors analyzed the negative effects that the electricity insecurities have caused to the advancement of the industrial sector of the Nigerian economy. It was concluded that concerted efforts must be made to improve the power sector operations for efficient manufacturing productivity and industrial advancements.

Ajao, Ajimotokan, Popoola, and Akande (2009) gave an overview of the present state of Nigeria's power system. The authors highlighted the level of uncertainty that is obtainable in the Nigerian power system. According to the authors, there is an urgent need to adopt renewable and decentralized energy generation systems for the purpose of continued revenue generation by conserving the country's crude oil and natural gas for export purposes. The authors mentioned some of the advantages of renewable energy technologies as the simplicity of installation, ease of maintenance, and also, their enhanced environmental friendliness over fossil fuel-dependent power generation systems.

Amadi (2017) studied the benefits of adopting distributed generation systems in improving the security and reliability of Nigeria's power grid. The author highlighted the challenges that are facing the adequate and reliable generation of electricity in Nigeria, and also, the challenges facing the successful implementation of distributed generation, stating the lack of incentives from the government to support and motivate the implementation of such projects as one of the pressing issues. The author also discussed the various utilizable energy sources and renewable energy potentials in Nigeria.

Ahmed and Gidado (2008) studied the benefits of implementing stand-alone power systems in curbing high transmission and distribution losses that are incurred due to the dispersed nature of rural electricity consumptions that makes it highly cost intensive to build adequate transmission and distribution facilities to achieve a high electrification rate in the country. The authors highlighted how adopting renewable energy sources would help in deferring investments in the transmission and distribution sectors, and the environmental benefits of migrating to renewable sources which include the reduction in global carbon dioxide emissions. Performance charts that reveal the PV energy outputs for different locations in Nigeria were developed to enable renewable energy power system designers and developers to make informed decisions on the energy viability of the desired locations.

Ogunnubi, Ajala, and Idehen (2017) proposed the installation of stand-alone microgrids for the purpose of meeting the ever-increasing load demand in the urban regions of Nigeria. The authors identified voltage and frequency instabilities, and grid unreliability as the reasons for proposing plug-and-play microgrids to avoid the negative impacts of the main grid's instability on the microgrids. The microgrids are expected to operate in stand-alone mode during grid fault conditions. According to the authors, one of the benefits of decentralized generation is the ability of a prosumer to generate revenue when excess power is sold to willing consumers.

Okundamiya and Omorogiuwa (2016) analyzed the techno-economic and environmental potentials of a stand-alone wind-diesel microgrid in Maiduguri, the capital of Bornu State, in the northern part of Nigeria. The cost implications, energy potentials, and CO_2 emissions of wind-diesel microgrid was compared to that of wind-diesel-battery, diesel-battery, and diesel-only micogrids using the cost of diesel, average wind speed of Maiduguri, and the cost of purchasing the optimal battery storage size for meeting the load demands. The authors concluded that the proposed wind-diesel microgrid can provide improved power reliability, cost saving, and reduced CO_2 emissions when compared to the diesel-only microgrid.

Akpan, Isihak, and Udoakah (2013) studied the viability of off-grid photovoltaic systems in improving electricity access in the north-east of Nigeria. According to the authors, the north-eastern part of Nigeria which consists of Adamawa, Bauchi, Borno, Gombe, Taraba, and Yobe is said to have an average electrification rate of about 28.4%. Lifecycle approach was used in this study to estimate the lifecycle cost of an off-grid electrification project using photovoltaic panels and comparing the cost to the cost of paying for grid electricity over the same period of time. The authors concluded that the project is not economically viable as the payback time is more than the operational life of the photovoltaic system, but however, the project becomes viable if the cost of PV panels reduces, and there is adequate government support through the provision of low-interest loans and other incentives.

Nwulu and Agboola (2011) reviewed the state of Nigeria's power system by observing the electricity generation and consumption patterns over some years, and the potentials of renewable energy sources for power generation. According to the authors, the dilapidated state of power infrastructures, and lack of maintenance culture over the years are some of the factors contributing to the incessant shortage in the supply of electricity in Nigeria.

Nwaneto, Akuru, Udenze, Awah, and Okoro (2018) in their research paper, discussed the economic implications of utilizing renewable energy sources for electricity generation in Nigeria, by linking the effects of macroeconomic factors such as investments, cost of energy, industrial competitiveness, energy efficiency, changes in GDP, employment, income level, and standard of living improvements. The authors highlighted the factors that motivate energy transitions, among which are population growth, depletion of existing energy resources, the need to reduce the cost of energy and all associated inefficiencies during energy production. The importance of energy efficiency in enhancing sustainability in the Nigerian power system was also discussed.

Akuru and Okoro (2010) researched on the renewable energy investments in Nigeria by reviewing the Renewable Energy Master Plan (REMP). REMP is a document provided by the Energy Commission of Nigeria (ECN), and the United Nations Development Program (UNDP) to provide the details of Nigeria's renewable energy adoption plans for energy sustainability achievements. The authors listed the unavailability of reliable renewable energy data as one of the problems affecting renewable energy investments in Nigeria. The REMP was conceived in 2005, and the successful implementation of the plans therein will result in the installation of 2945 MW of wind, solar thermal, small hydro and biomass by 2025. The authors expressed concerns about the realization of REMP by 2025 due to the fact that it was yet to commence as of 2010.

Idris, Lamin, Ladan, and Yusuf (2012) analyzed wind energy potentials in Nigeria using wind data from 14 states. The lack of government policies and incentives that encourage the adoption of renewable sources for power generation were identified as part of the major problems preventing Nigeria from transitioning to large scale power generation using energy from the wind. The authors in their work identified some measures that will lead to the inclusion of wind energy in the energy mix of Nigeria to meet the growing energy demands, improve energy security, and align with the global trends of green energy growth. The authors also identified some of the challenges affecting the large-scale deployment of wind energy in Nigeria as lack of financial and other fiscal incentives, lack of skilled manpower, lack of indigenous manufacturing capability, and also, the lack of policies and institutional framework to encourage investments and deployment of wind energy technology.

Okoronkwo, Ojo, and Davidson (2016) analyzed the 10 MW pilot wind farm installation in Katsina State, in the northern part of Nigeria. The wind farm covers 200 hectares of land with a total of 37 squirrel cage induction generator (SCIG) wind turbines, with each of them having a power rating of 275 kW, and a tower height of 55 meters. As of 2016 when the authors' report was published, the project was yet to be completed. The project is expected to augment the power supply in Katsina State after its completion.

Akuru, Okoro, and Chikuni (n.d.) reviewed the dire consequences of Nigeria's over-dependence on fossil fuel as its primary energy source, and the impacts on climate change. The authors predicted that the emission of CO_2 in Nigeria will significantly increase in the coming years due to teeming population growth, and over-dependence on fossil fuel. According to the authors, gas flaring by oil and gas producing companies is one of the major contributors of CO_2 emissions in Nigeria. Stringent penalties were recommended for defaulters as a measure to curb the incessant flaring of gases by these companies.

2.3. The Generation System

The generation system comprises of 28 grid-connected power stations which are majorly fossil fuel dependent. As shown in Fig. 1, thermal power stations make up 86% of the total installed generation capacity with a total size of 13,627 MVA. Presently, the only grid-connected power generation type that can be considered as renewable is hydropower, and it is only14% of the total installation, with a capacity of 2,242 MVA. Due to the poor power factor of the grid which is a little above 0.8, the total installed generation capacity in megawatt is reported by TCN as 12,910.40 MW.

The inception of the generation of electric power in Nigeria was in Lagos in 1896. In 1929, Nigeria Electric Supply Company (NESCO) was established and operated as the country's utility company. In 1951, Electric Corporation of Nigeria (ECN) was established to replace NESCO, with a mission to ensure the adequate supply of electricity to consumers. Niger Dams Authority (NDA) was established in 1962 for the development of hydropower stations. In 1972, the National Electric Power Authority (NEPA) was established with the responsibility of handling the country's generation, transmission, and distribution (Nigerian Electricity Regulatory Commission [NERC] n.d.). NERC was established in 2005 to ensure the regulation of the electric power industry in Nigeria, and in 2010, Nigeria Bulk Electricity Trading Plc (NBET) was established to engage in the purchase and resale of electric power and ancillary services from the independent power producers, and from the successor generation companies (PwC, 2016). Figure 5 below shows the timeline of the evolution of Nigeria's power system from the year 2005 to 2015.

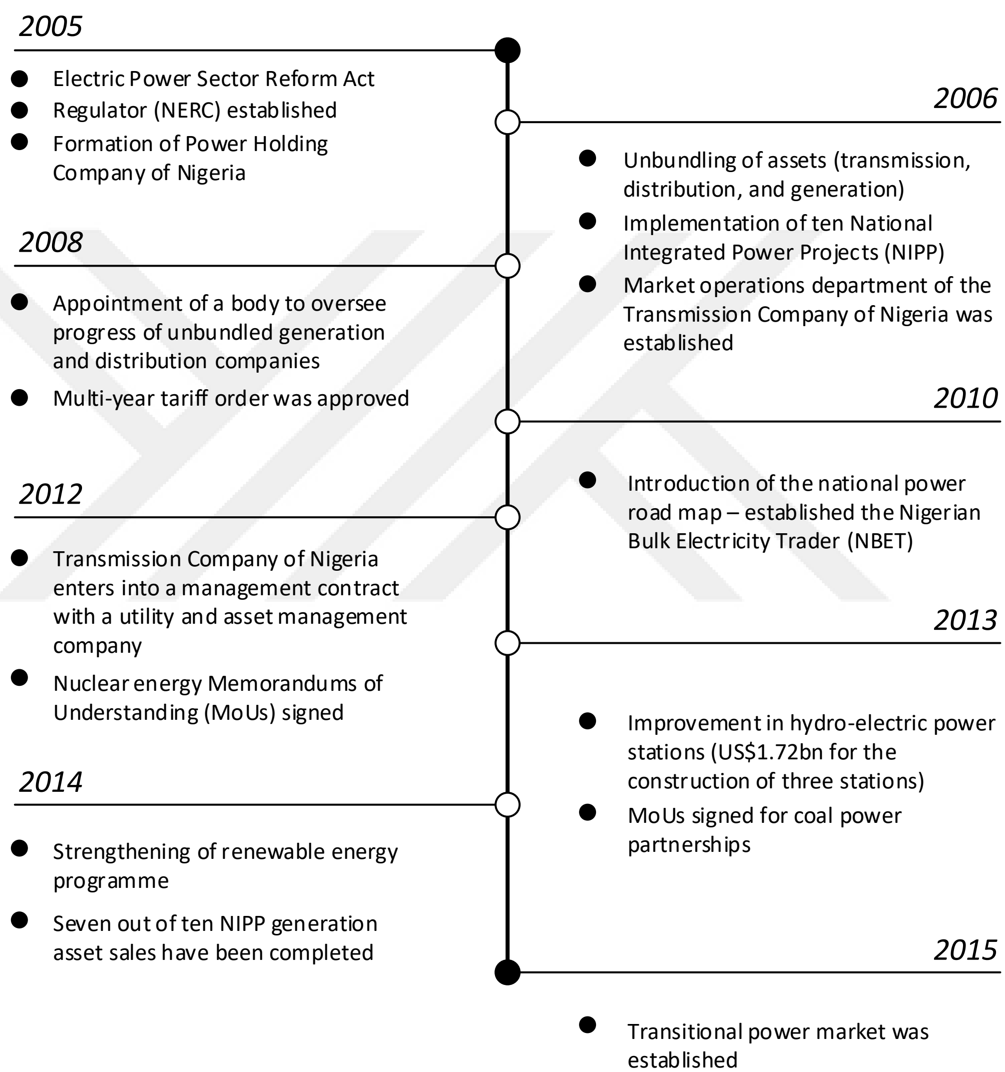


Fig. 5. Nigerian power sector evolution (source: PwC, 2016)

Due to the passage of the Electric Power Sector Reform Act in 2005, through which the country's power system was disbanded into six generation companies (GenCos), eleven distribution companies (DisCos), and a single transmission company (TCN) that is solely owned and controlled by the government. The GenCos and DisCos are currently being operated by private companies. Table 4 shows the list of GenCos and their privatization statuses.

Table 4. Generation Companies (GenCos) (source: NERC, n.d.)

GenCo	Type	Privatization Status
Afam Power Plc	Gas	100% Sold
Sapele Power Plc	Gas	51% Sold
Egbin Power Plc	Gas	100% Sold
Ughelli Power Plc	Gas	100% Sold
Kainji/Jebba Power Plc	Hydro	Long Term Concession
Shiroro Power Plc	Hydro	Long Term Concession

As can be seen in Table 5 below, apart from the privatized GenCos, Independent Power Producers (IPPs) and the generation stations established under the National Integrated Power Projects (NIPP) also contribute to the total power generation on the grid.

Table 5. Grid-Connected Generation Stations (source: TCN, n.d.; Fichtner, 2017)

Station			Turbine Type	Operation Start Date	Number of Units Installed	Rating (MVA)	Power Factor
1	Kainji (Hydro)	Privatized Companies	Hydro	1968 -1976	8	822.00	0.95
2	Jebba (Hydro)		Hydro	1983 – 1988	6	714.00	0.85
3	Shiroro (Hydro)		Hydro	1990	4	706.00	0.85
4	Egbin (Steam)		Steam	1985 – 1987	6	1474.80	0.90
5	Sapele (Steam)		Steam	1990	6	808.82	0.90
6	Delta (Gas)		GT OC	1990 – 2005	18	1249.20	0.80
7	Afam IV & V (Gas)		GT OC	1982 – 2002	8	985.38	0.85
8	Geregu (Gas)		GT OC	2007	3	522.00	0.85
9	Omotosho (Gas)		GT OC	2007	8	380.00	0.80
10	Olorunsogo (Gas)		GT CC	2007	8	384.00	0.80
11	Geregu NIPP (Gas)	NIPP	GT OC	2013	3	522.00	0.85
12	Sapele NIPP (Gas)		GT OC	2011	4	440.00	0.90
13	Alaoji NIPP (Gas)		GT OC	2013 – 2014	4	565.00	0.85
14	Olorunsogo NIPP (Gas)		GT CC	2011 – 2012	6	947.72	0.80

Station			Turbine Type	Operation Start Date	Number of Units Installed	Rating (MVA)	Power Factor
15	Omotosho NIPP Gas		GT OC	2012	4	660.00	0.80
16	Odukpani NIPP (Gas)		GT OC	2015	5	706.25	0.80
17	Ihovbor NIPP (Gas)		GT OC	2013 – 2014	4	565.00	0.80
18	Gbarain NIPP (Gas)		GT OC	2016	1	141.25	0.80
19	Okpai (Gas/Steam)		GT CC	2005	3	630.00	0.85
20	Azura - Edo IPP (Gas)		GT OC		3	573.75	0.80
21	Afam VI (Gas/Steam)		GT CC		4	855.00	0.80
22	Ibom Power (Gas)		GT OC	2009 – 2016	3	237.25	0.80
23	A.E.S (Gas)	IPP	GT OC	2002	9	355.92	0.90
24	ASCO (Gas)		GT OC		2		0.80
25	Omoku (Gas)		GT OC	2006	6	187.50	0.80
26	Trans-Amadi (Gas)		GT OC	2010	4	125.00	0.80
27	Rivers IPP (Gas)		GT OC	2012	1	225.00	0.80
28	Paras Energy (Gas)		GT OC		8	85.75	0.80
					149	**15868.59**	

From the 28 power generation stations listed in Table 5, 10 stations belong to the privatized generation companies, 8 stations are NIPP generation stations, and the remaining 10 stations are independent power producers. In an effort to mitigate the shortage of electricity, in 2004, Niger Delta Power Holding Company (NDPHC) was established with the mandate to oversee the construction of 10 NIPP power generation stations, transmission and distribution infrastructures in the regions with critical power supply needs (NERC, n.d.). The IPP power stations have always been controlled by private companies, even before the establishment of the GenCos. As a result of the need for action outside the grid-connected areas that are serviced by the DisCos, the Rural Electrification Strategy and Implementation Plan (RESIP) was approved in 2016 with the primary objective of expanding access to electricity in rural areas as rapidly as possible in a cost-effective manner through the use of both grid and off-grid approaches (World Bank, 2018).

According to the information provided in the daily operational report from TCN for 28/01/2019, the peak generation for the day was 4,490.8 MW, and the generation capacity of all the power stations combined was 4,764.8 MW. The installed generation capacity is currently put at 12,910.40 MW. The total spinning reserve of the power system is 295 MW. There is a total of 149 generation units from all the 28 grid-connected power stations. Despite that there is a total of 149 units, for the particular day under review, only 51 units with a total capacity of 5,140.5 MW were available. The reasons for the unavailability of generation units could be any of system components faults, forced outages due to gas constraints, low head water elevation, maintenance, frequency management, or decommissioning. Faults such as stator winding failure, oil leakage, burnt generator windings, boiler problems, vibration, and low gas pressure are common faults on the power system. AES power station, for example, has been out of production since 2014, and Asco power station is shut down due to leakage in the furnace. Another reason for the low efficiency and reliability of the power generation system is the age of the power plants. Some of the power plants have passed their operational lifetime and require major overhauling to restore them to good operational conditions. The age of the power plants is a contributory factor in the frequent generator unit breakdowns and overall downtime. In the case of gas turbines, the end of operational life is reached latest after more than 200,000 hours of operation, or 30 years of after commercial operation date (Fichtner, 2017).

Apart from overhauling and regular maintenance of the power plants, installation of new power generation stations is required to mitigate the power generation deficiencies presently inherent in Nigeria’s power system. The wheeling capacity of the transmission system is small, and it prevents the efficient transmission of the generated power across the grid. If the power plants were more efficient, and more power is generated, it will be difficult to transmit the generated power with the present transmission wheeling capacity. To reduce the burden on the transmission system, and to be able to defer transmission investments, it is economically appropriate to install distributed generators at the critical areas for customer satisfaction, and for transmission system loss reductions. Because of the need to reduce the impacts of global warming, renewable energy-based distributed generators with storage systems, installed close to the point of use will help in meeting consumers power needs, and at the same time, perform ancillary services on the grid by contributing to voltage and frequency stabilities.

2.4. The Transmission System

Nigeria's transmission network consists of high voltage substations with a transmission wheeling capacity of 8100 MW and over 20,000 km of transmission lines (NERC, n.d.). The transmission system is fully owned and controlled by the government. Due to the unbundling and privatization of Nigeria's electricity infrastructure in 2005, 6 generation companies (GenCos), a transmission company, and 11 distribution companies (DisCos) were established with the aim of achieving a better grid performance through the operation of these companies. Transmission Company of Nigeria (TCN) is the only company responsible for the transmission of power from the GenCos to the DisCos. TCN is responsible for evacuating the electric power generated by the generating companies(GenCos) and wheeling it to the distribution companies (DisCos) (NERC, n.d.). The transmission system is radial and fragile and has large reactive power flowing through it because of the dispersed nature of some of the load areas which necessitates the connection of long transmission lines for wheeling power to the distribution feeders. The Nigerian transmission network is characterized by very lengthy transmission lines and feeders which make voltage control difficult (Akpojedje et al., 2016). The entire transmission infrastructure is essentially radial, without redundancies, thus, creating inherent reliability issues (NERC, n.d.). As can be observed in Fig. 3 above, the generation stations are not evenly distributed across the country, leaving areas such as the north-central and the north-eastern parts of Nigeria with no generation capacities. With most of the generation stations located in the southern part of the country and only the hydroelectric power stations located in the north-western part, long transmission lines are needed to wheel power to the other regions where power is needed. For more reliable and optimal operation of the transmission system, it will be highly necessary to install new power plants in the areas with a lack of power generation. To supply the loads in the areas with little or no generation, long 330 kV transmission lines are built (mostly radial system), and as a result, causing voltage regulation problems, and excessive reactive power flowing through the lines (Fichtner, 2019). The excessive reactive power flowing through the transmission lines reduces the active power carrying capabilities of the lines, causing the lines to be overloaded, and resulting in a transmission system with a high-power loss, and low efficiency. The lengthy transmission network has reduced the maximum power transfer capability on the lines, thereby reducing the margin between the planned power transfer and the maximum limit at which the lines are susceptible to transient and dynamic instabilities (Akpojedje et al., 2016). With an average transmission loss of approximately 7.4%, the transmission losses across the network are high compared to emerging countries' benchmarks of between 2 and 6% (NERC, n.d.). The current practice by TCN is to shed the loads that cannot be served either due to lack of generation or circuit overloads (Fichtner, 2017).

Three operational departments are incorporated to form the Transmission Company of Nigeria (TCN), and they are Transmission Service Provider (TSP), System Operations (SO), and Market Operations (MO). The TSP oversees the development and maintenance of the transmission infrastructure, SO manages the flow of electricity throughout the power system from generation to distribution companies, and MO is responsible for the administration of the electricity market, and promoting efficiency in the market (NERC, n.d.).

2.5. The Distribution System

Electricity distribution to consumers is controlled by the distribution companies (DisCos). There are 11 DisCos, and the choice of DisCo to service a customer is determined by the customer's location. The DisCos are privatized companies, and they are responsible for selling electricity to the consumers. The primary distribution voltages are 33 kV and 11 kV, and the secondary distribution voltages are 415 V for three-phase customers, and 230 V for single-phase customers. The DisCos and the areas they serve are shown in Fig. 6 below.

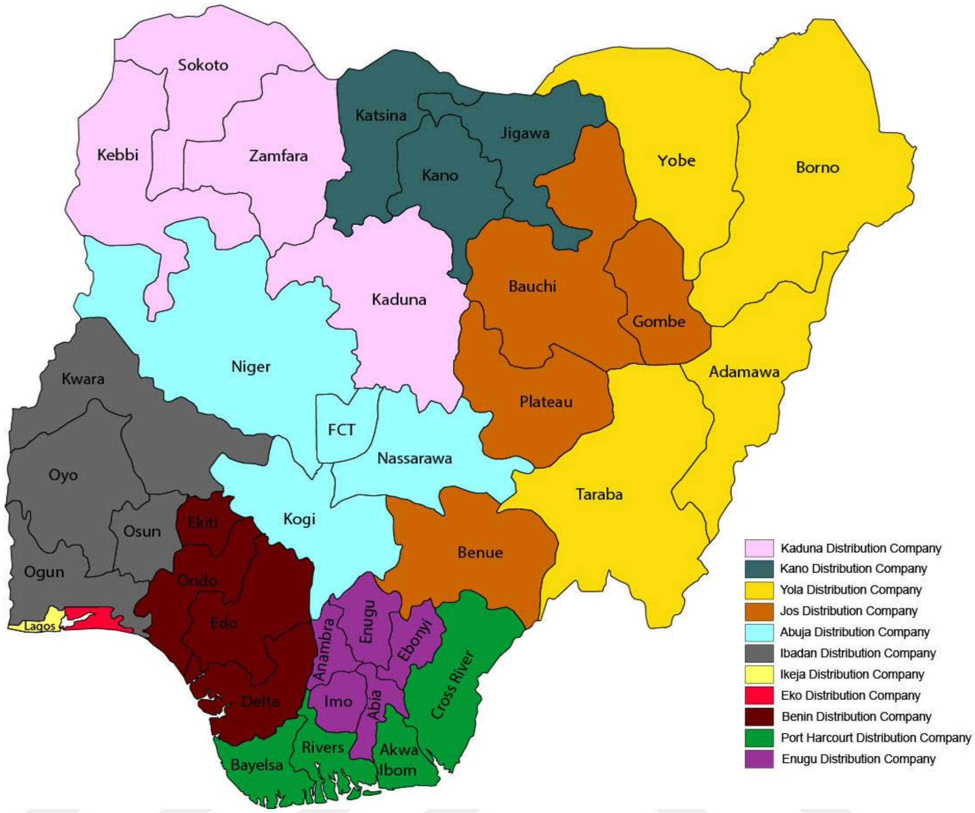


Fig. 6. Electricity distribution companies (DisCos) (source: NERC, n.d.)

Each of the DisCos is allocated a percentage of the total power available on the grid. The percentage of the grid power available to each DisCo is not constant but changes regularly based on the load requirements of the electricity customers. Although the generation capacity of the Nigerian power system is low, the transmission and distribution systems contribute to further reducing the amount of power available to the consumers. About 7% of generated power is lost through transmission process and a further 12% is lost through distribution, resulting in a cumulative transmission and distribution loss of about 19% of the generated power (PwC, 2016). Table 6 shows the daily DisCo load summary provided by TCN for 15/08/2017.

Table 6. Daily DisCo Load Summary for 15/08/2017 (source: TCN, n.d.)

Disco	**Actual Consumption (MW)**	**Percentage of Total Load**
Abuja	377.4	12.82
Benin	213	7.23
Eko	378.34	12.85
Enugu	210.11	7.14
Ibadan	371.28	12.61
Ikeja	496.37	16.86
Jos	141.93	4.82
Kaduna	177.2	6.02
Kano	258.1	8.77
Port Har.	229.25	7.79
Yola	91.6	3.11
	2944.58	**100.00**

INT'L Lines	**Min Load (MW)**	**Max Load (MW)**
Sakete	123	294
Niamey	70	80
Gazuoa	22.1	37

The percentage of load consumption by the DisCos is not entirely constant but is a reflection of the load requirements by the electricity consumers in the different areas. Despite that Nigeria has a deficiency in meeting the electricity needs of its immediate customers, it sells electricity to neighboring countries such as Togo, Republic of Niger, and the Republic of Benin through a bilateral agreement. Nigeria sells around 300 MW of power to its international customers through three international transmission lines. The total energy generated on 15/08/2017 was 86764.83 MWh, and the average energy generated per hour was 3615.20 MWh/h.

3. RENEWABLE ENERGY MICROGRID

3.1. An Overview of Renewable Energy Microgrids

The need to mitigate the effects of global warming by reducing the amount of carbon dioxide in the atmosphere is one of the motivations for migrating from fossil fuels to renewable energy sources for power generation. The growing concerns for primary energy availability and aging infrastructure of current electrical transmission and distribution networks are increasingly challenging security, reliability, and quality of power (Hatziargyriou, 2014). Apart from global warming, some other important reasons such as the finite nature of fossil fuels, the growing demand for energy, the free and inexhaustible nature of renewable energy, and the need to have a sustainable environment are the reasons why utilizing renewable energy sources for energy generation is very important. Renewable sources are free from nature, clean, environmentally friendly, and do not impact the environment negatively, unlike fossil fuels. It is expected that the exploitation of DERs would help to generate eco-friendly clean power with much lesser environmental impacts (Chowdhury, Chowdhury, and Crossley, 2009).

According to the European Technology Platform of Smart Grids, a microgrid is a platform that facilitates the integration of distributed generators (DG), energy storage systems (ESS), and loads to ensure that the power grid can supply sustainable, price-competitive, and reliable electricity (Gao, 2015). According to Hatziargyriou (2014), a microgrid is a system which comprises of low voltage (LV) distribution systems with distributed energy resources (DER) together with storage devices and flexible loads, which can be operated in a non-autonomous way if interconnected to the grid, or in an autonomous way if disconnected from the main grid. A microgrid should be able to operate in grid-connected mode during normal operations, and islanded mode during emergency operations. It is expected that during faults conditions on the grid, the microgrid should be able to securely disconnect from the main grid and operate autonomously while maintaining the operational voltage and frequency of the grid. Microgrids are now required to ride-through minor faults on the grid while providing electricity to critical loads. The power sources of distributed generators are usually connected to the distribution system, which is typical of voltages 230/415 V up to 145 kV (Chowdhury et al., 2009). Microgrids can provide network support in times of stress by relieving congestion and aiding restoration after faults (Hatziargyriou, 2014). In power systems operations, distributed generators or microsources can be both renewable energy based, or fossil fuel based, but for the purpose of mitigating GHG effects while also considering the rate of depletion of fossil fuel reserves, migrating to renewable means for sustainable electricity generation is highly necessary. DERs are generally modular units of small capacity and usually located close to the load (Chowdhury et al., 2009). The increasing use of renewable energy not only helps to alleviate fuel poverty but also promotes decentralized power generation, thereby reducing the dependence on conventional grid-based energy sources (Diaz-Gonzalez, Sumper, and Gomis-Bellmunt, 2016). The conventional grid is a passive network which only permits the flow of current from the power stations to the loads, but with the introduction of microgrids to the main grid, the network becomes active, and current flow becomes bidirectional with the aid of power electronic converters. From an operational point of view, the microsources must be equipped with power electronic interfaces and controls to provide the required flexibility to ensure operation as a single aggregated system and to maintain the specified power quality and energy output (Chowdhury et al., 2009). Due to the intermittent nature of renewable sources such as wind and solar, the energy generated from these sources is not dispatchable as wind energy and solar radiation are not available throughout the day, choosing the appropriate storage system will improve the operations of the microgrid. Some of the benefits of renewable energy microgrids are GHG reduction, voltage and frequency regulations, energy loss reduction, peak load shaving, and reliability enhancement (Hatziargyriou, 2014). A layout of the connection of a microgrid to the main grid is shown in Fig. 7.

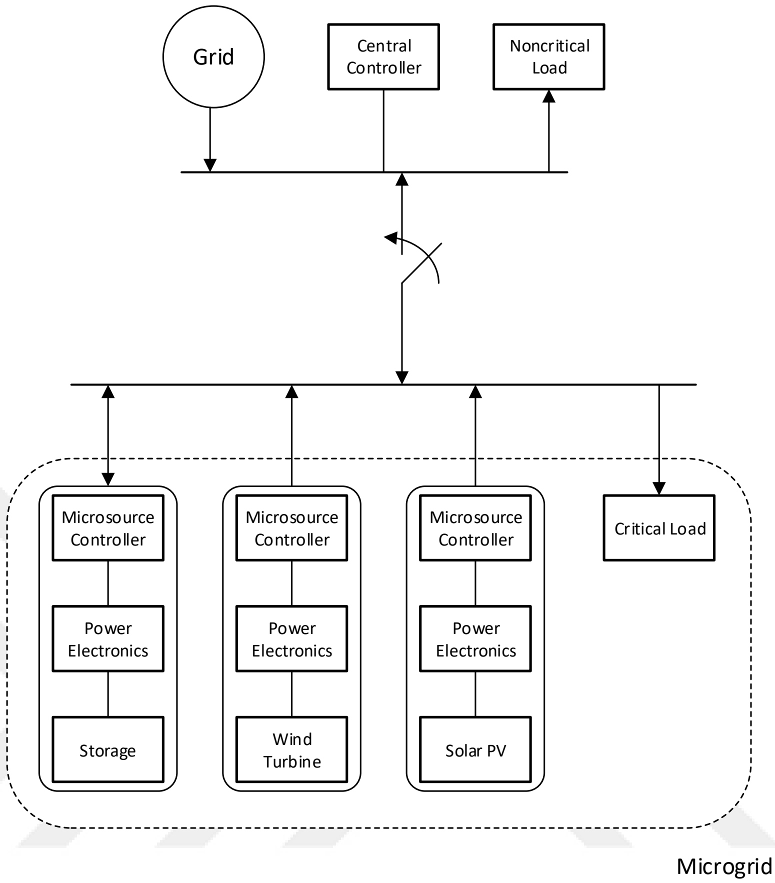


Fig. 7. Microgrid Layout

In Fig. 7, the connection of renewable energy sources, critical load, and storage system is shown. In a microgrid, the distributed generators and the loads are at proximity to each other, and the connection to the grid is usually done at distribution voltage levels. The microgrid and the main grid are connected through the point of common coupling (PCC) circuit breaker to disconnect the microgrid from the main grid in the case of a fault. The active network infrastructure employs a central controller (CC), and microsource controllers (MC) for effective decision making on the power system. The central controller receives information such as voltage, current, and power status from the DGs, ESSs, and controllable loads in real-time, and the data collected is used to determine the interoperability of the main grid with the microgrids. The central controller executes the overall control of microgrid operation and protection through the microsource controllers by maintaining specified voltage and frequency at the load end through power factor and voltage control, and it ensures energy optimization for the microgrid (Chowdhury et al., 2009). The microsource controller plays the most important role in optimizing a microgrid by deciding how much power is needed to be imported from the utility network, and how many non-critical loads should be shed in critical conditions (Gao, 2015). The power electronic converters serve the purpose of power conditioning to convert the electricity produced by the microsources to a form compatible with the main grid. The PV system, for example, produces dc voltage which is converted to AC voltage by the power electronic converter before being fed to the grid.

3.2. Wind Energy System

The process of utilizing wind energy for electricity generation involves the conversion of the kinetic energy in the wind to mechanical power through aerodynamic processes using the rotors, and the conversion of the mechanical energy in the rotors to electrical energy using a generator. In modern wind turbines, the actual conversion process uses the basic aerodynamic force of lift to produce a net positive torque on a rotating shaft, resulting first in the production of mechanical power and then in its transformation to electricity in a generator (Manwell and McGowan, 2009). The wind is a form of energy which results from the uneven heating of the earth surface by the sun. The uneven heating of the earth's surface results in pressure differences which is responsible for the wind. The spatial variations in heat transfer to the earth's atmosphere create variations in the atmospheric pressure field that cause air to move from high to low pressure (Manwell and McGowan, 2009). Local winds are due to local pressure differences and are influenced by topography, the friction of the surface due to mountains, valleys, etc. (Nelson, 2009).

The wind turbine is the most important component of a wind energy conversion system. Wind turbines are classified as vertical axis wind turbines (VAWT) and horizontal axis wind turbines (HAWT). HAWTs are driven by lift force, while VAWTs are driven by drag force. Vertical axis wind turbines can further be classified as savonius, darrieus, and giromill while horizontal axis wind turbines can be classified as upwind and downwind wind turbines (Nelson, 2009). Horizontal axis wind turbines are more economically viable for electricity production than vertical axis wind turbines. The upwind wind turbine is orientated to face the wind, and this is achieved through the yaw mechanism. Rotor, nacelle, and tower are the most important parts of a wind turbine. The rotor can have two or more blades, and it functions to convert the linear motion of the wind into rotational energy that can be used to drive a generator. The rotor of a HAWT is usually connected to the generator through a multiple-ratio gearbox to increase the rotational speed from the rotor to a level suitable for power production in the generator. The nacelle houses the drive-train, the generator, and the control system of the wind turbine, and also protects its contents from the weather. HAWTs are further divided into fixed speed (type 1), limited variable speed (type 2), or variable speed with either partial (type 3) or full (type 4) power electronic conversion (Glover, Sarma, and Overbye, 2012). The generators used in wind turbines are synchronous generators, permanent magnet synchronous generators, and induction generators; including the squirrel-cage type, and the wound rotor type. Wind energy differs from location to location, and the knowledge of the wind energy potentials of proposed locations is necessary for deciding the appropriate sites for wind turbine installations. Among the HAWTs, the doubly-fed induction generator (DFIG) wind turbine (type 3) is more prominent in wind energy applications. In practice, a maximum of about 45% of the available wind power is harvested by the best modern horizontal axis wind turbines (Manwell and McGowan, 2009).

The power in the wind is a function of the air density. Air density is a function of temperature and pressure, and they both vary with height. The power in the wind depends on the amount of air (volume), the speed of air (velocity), and the mass of air (density). The turbine output power, P_T, is given in (1).

$$\text{Turbine Power Output, } P_T = {}^{1}/_{2}\, \rho A V^3 C_P \qquad (1)$$

Where ρ is the density of air, A is the swept area of the turbine rotor, V is the velocity of air, and C_P is the power coefficient. Power coefficient, C_P, is the ratio of the power extracted by the turbine to the total power contained in the wind. The rotor power performance is usually characterized by its power coefficient (Manwell and McGowan, 2009). As described by Betz limit, the maximum theoretical rotor power coefficient, $C_{P,max}$, is $16/27$, which in essence, implies that the output power from a wind turbine cannot be more than 59.26% of the total power available in the wind.

The knowledge of the energy potentials of a place is very important in selecting the appropriate sites for the installation of wind turbines. The Wind Resource Assessment (WRA) provides information about the strengths of wind speeds and the energy content in them, and it also guides in the selection of the appropriate type of wind turbine design for deployment at a given location or in a region (Manwell and McGowan, 2009). The suitability of a site for wind energy production and the amount of energy that can be obtained from such a site can be estimated using statistical methods. Two of the most popular methods in literature for wind resource assessment are Rayleigh and Weibull distributions. Rayleigh distribution only requires the average wind speed value to determine the probability density function, $p(U)$, which can be used to determine the frequency of occurrence of wind speed. The formula for finding the probability density function, $p(U)$, according to the Rayleigh distribution method is given in (2).

Probability density function, $p(U) = \frac{\pi}{2}\left(\frac{U}{\overline{U}^2}\right) exp\left[-\frac{\pi}{4}\left(\frac{U}{\overline{U}}\right)^2\right]$ (2)

Where U represents a range of wind speeds from 0 m/s to 25 m/s, and $\overline{U}$ represents the site's average wind speed. Table 7 shows the average wind speeds of different states in Nigeria, their corresponding wind power densities, and the wind energy densities at 50 meters and 100 meters. The average wind speeds of the different states were obtained from the Global Wind Atlas (GWA, n.d.). The wind power densities, (P/A), and the wind energy densities, (E/A), can be obtained as in (3) and (4) respectively. In the calculations, the density of air, ρ, is assumed to be 1.2 kg/m^3, and time, t, equals 8760 hours.

Wind power density, (P/A) = $\sum_{25}^{U=0} \left({}^{1}/_{2}\, \rho U^3 p(U)\right)$ (3)

Wind energy density, (E/A) = $\left({}^{P}/_{A}\right) * t$ (4)

Table 7. Nigeria's Wind Energy Data (source: GWA, n.d.)

	50 m Height			**100 m Height**		
State	**Wind Speed (m/s)**	**Wind Power Density (W/m^2)**	**Wind Energy Density $(kWh/m^2/yr)$**	**Wind Speed (m/s)**	**Wind Power Density (W/m^2)**	**Wind Energy Density $(kWh/m^2/yr)$**
Sokoto	5.14	155.58	1362.89	6.40	300.29	2630.58
Zamfara	4.84	129.90	1137.91	6.05	253.70	2222.40

	50 m Height			100 m Height		
State	**Wind Speed** (m/s)	**Wind Power Density** (W/m^2)	**Wind Energy Density** $(kWh/m^2/yr)$	**Wind Speed** (m/s)	**Wind Power Density** (W/m^2)	**Wind Energy Density** $(kWh/m^2/yr)$
Katsina	5.01	144.07	1262.08	6.21	274.35	2403.35
Kano	4.69	118.19	1035.36	5.66	207.74	1819.78
Jigawa	4.71	119.71	1048.66	5.88	232.91	2040.31
Yobe	5.04	146.68	1284.88	6.20	273.03	2391.76
Borno	4.97	140.65	1232.09	6.16	267.78	2345.79
Kebbi	4.61	112.25	983.28	5.97	243.77	2135.42
Niger	4.11	79.54	696.78	5.14	155.58	1362.89
Kaduna	4.83	129.10	1130.87	5.97	243.77	2135.42
Bauchi	4.56	108.63	951.63	5.51	191.66	1678.90
Gombe	5.31	171.53	1502.64	6.30	286.45	2509.30
Adamawa	5.5	190.61	1669.78	6.29	285.09	2497.37
Kwara	4.6	111.52	976.89	5.44	184.44	1615.73
FCT	3.87	66.41	581.71	4.56	108.63	951.63
Nasarawa	4.45	100.96	884.41	5.31	171.53	1502.64
Plateau	5.68	209.95	1839.14	6.57	324.83	2845.52
Oyo	4.63	113.71	996.13	5.45	185.46	1624.65
Osun	4.18	83.68	733.00	4.84	129.90	1137.91
Ekiti	4.53	106.50	932.97	5.13	154.68	1354.95
Kogi	4.95	138.96	1217.27	5.68	209.95	1839.14
Benue	4.61	112.25	983.28	5.52	192.70	1688.06
Taraba	5.11	152.87	1339.17	5.93	238.90	2092.80
Ogun	3.92	69.01	604.55	4.77	124.34	1089.25
Ondo	4.21	85.49	748.89	4.79	125.91	1103.01
Edo	4.67	116.69	1022.17	5.38	178.41	1562.85
Enugu	4.76	123.56	1082.41	5.46	186.49	1633.61

	50 m Height			100 m Height		
State	**Wind Speed** (m/s)	**Wind Power Density** (W/m^2)	**Wind Energy Density** $(kWh/m^2/yr)$	**Wind Speed** (m/s)	**Wind Power Density** (W/m^2)	**Wind Energy Density** $(kWh/m^2/yr)$
Ebonyi	3.89	67.44	590.77	4.69	118.19	1035.36
Anambra	4.11	79.54	696.78	4.82	128.29	1123.86
Lagos	5.44	184.44	1615.73	5.57	197.98	1734.35
Delta	4.21	85.49	748.89	4.81	127.50	1116.88
Imo	3.72	58.98	516.66	4.46	101.64	890.38
Abia	3.52	49.97	437.72	4.16	82.48	722.52
Cross River	4.61	112.25	983.28	5.29	169.60	1485.73
Bayelsa	4.15	81.89	717.33	4.53	106.50	932.97
Rivers	4.36	94.96	831.82	4.94	138.12	1209.91
Akwa Ibom	4.11	79.54	696.78	4.57	109.35	957.90

3.3. Solar PV System

The energy from the sun is enormous, inexhaustible, free from nature, and can comfortably meet the world's energy needs. More energy from sunlight strikes the earth in 1 hour ($4.3 \times 10^{20}\ J$) than all the energy consumed on the planet in a year ($4.1 \times 10^{20}\ J$) (Foster et al., 2009). Solar PV systems utilize the energy from the sun for electricity generation. The major advantages of a PV system are sustainable nature of solar energy as fuel, minimum environmental impact, a long functional lifetime with minimum maintenance, and silent operation (Chowdhury et al., 2009). The operational life of the PV cells that are currently being produced is about 40 years. The energy produced by a PV system is directly proportional to the amount of solar radiation available from the sun. The PV system is characterized with high installation cost and low energy efficiency. The most widely used material for the various types of fabrication is crystalline silicon, representing over 90% of the global commercial PV module production in its various forms (Foster et al., 2009). Solar energy reaches the PV cell in two components, direct and diffuse. The direct component is about 85% and it comes through direct radiation, while the diffuse component is about 15%, and it comes through scattered diffusion in the atmosphere (Chowdhury et al., 2009). Solar power is intermittent, and is only available during the daylight hours, having the appropriate storage system size on the network will allow the continuous supply of electricity during the periods without sunlight. The storage system stores the excess power produced by the PV system, supplies the required power to operate the loads, and acts as a voltage stabilizer in the electrical system (Foster et al., 2009). Equation (5) shows the relationship between Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), and Diffuse Horizontal Irradiance (DHI). GHI is the amount of terrestial irradiance that is falling on a surface that is horizontal to the surface of the earth. The main factors affecting the amount of insolation incident upon a solar surface are orientation, mounting angle with respect to horizontal, and climate conditions (Foster et al., 2009).

$$GHI = DNI \cos\theta + DHI \tag{5}$$

Where θ is the incident angle of the solar radiation. The solar irradiance values of the 36 states in Nigeria, including the Federal Capital Territory (FCT), are given in Table 8 as obtained from Global Solar Atlas (GSA, n.d.).

Table 8. Nigeria's Solar Irradiance Data (source: GSA, n.d.)

States	**GHI** $(\boldsymbol{kWh/m^2/day})$	**DHI** $(\boldsymbol{kWh/m^2/day})$	**DNI** $(\boldsymbol{kWh/m^2/day})$
Sokoto	5.83	2.80	4.13
Zamfara	5.84	2.83	4.12
Katsina	5.95	2.80	4.32
Kano	5.92	2.80	4.24
Jigawa	5.95	2.80	4.29
Yobe	5.97	2.75	4.33
Borno	5.92	2.69	4.41
Kebbi	5.66	2.86	3.77
Niger	5.30	2.93	3.17
Kaduna	5.69	2.82	3.87
Bauchi	5.87	2.75	4.25

States	GHI ($kWh/m^2/day$)	DHI ($kWh/m^2/day$)	DNI ($kWh/m^2/day$)
Gombe	5.87	2.72	4.28
Adamawa	5.75	2.70	4.13
Kwara	5.15	2.94	2.90
FCT	5.16	2.88	3.05
Nasarawa	5.25	2.89	3.13
Plateau	5.75	2.71	4.04
Oyo	4.71	2.93	2.33
Osun	4.66	2.93	2.26
Ekiti	4.88	2.92	2.57
Kogi	5.03	2.90	2.79
Benue	5.01	2.92	2.77
Taraba	5.37	2.85	3.37
Ogun	4.57	2.93	2.14
Ondo	4.70	2.93	2.30
Edo	4.69	2.93	2.28
Enugu	4.77	2.93	2.44
Ebonyi	4.79	2.93	2.44
Anambra	4.70	2.93	2.30
Lagos	4.80	2.84	2.56
Delta	4.53	2.88	2.13
Imo	4.55	2.92	2.12
Abia	4.59	2.90	2.20
Cross River	4.66	2.89	2.30
Bayelsa	4.36	2.80	2.04
Rivers	4.39	2.81	2.05
Akwa Ibom	4.42	2.85	2.05

Table 8 gives an idea of the solar energy potentials of Nigeria. As can be seen in (5), GHI is a very important parameter in sizing solar power installations, and it can be obtained from DNI, DHI, and the incident angle of the solar radiation. If Sokoto is taken as an example, with a 1kWp solar panel, electricity can be generated from the sun for 5.83 hours in a day. A pictorial representation of the GHI of Nigeria is shown in Fig. 8.

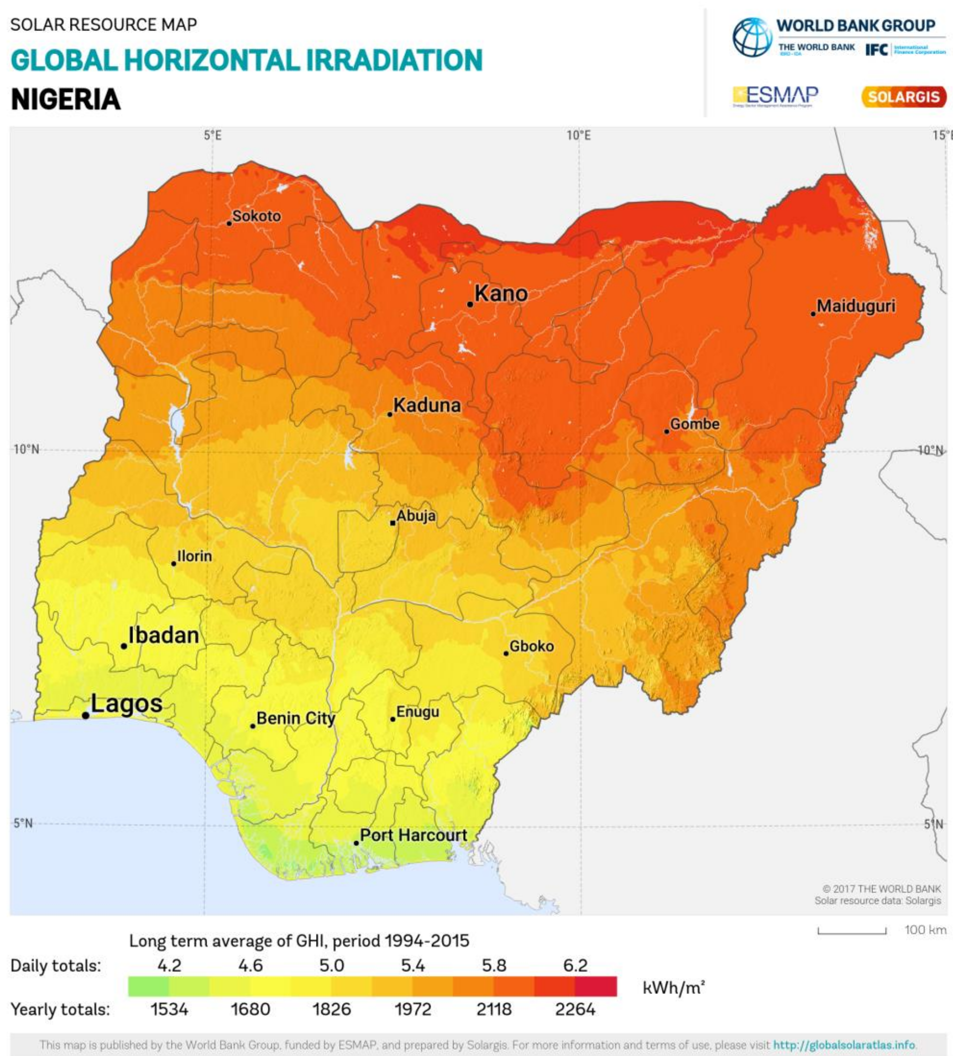


Fig. 8. Nigeria's Global Horizontal Irradiation map (source: GSA, n.d.)

3.4. Energy Storage Systems

Wind and solar energy are not dispatchable due to the intermittent nature of the wind and the sun. Therefore, the addition of energy storage systems with renewable energy sources will improve the overall operations of the microgrids. For a microgrid to operate satisfactorily both in grid-connected and islanded modes, optimal sizing of energy storage systems is of utmost importance. Undersizing the storage system will inhibit the operations of the microgrid while oversizing it will result in avoidable additional costs. The smooth transition of a microgrid to island operation with no loss of load is only possible with large storage or generation redundancy (Hatziargyriou, 2014). Energy storage systems can help to balance the difference between load demand and energy supply, meet load demands during power interruptions, thereby increasing the efficiency of the power system. The energy storage systems in microgrids also provide benefits for power quality, voltage regulation, reactive power support, and operating reserves (Gao, 2015). Some of the applications of storage systems are load following, peak shaving, transmission curtailing, and time shifting (Diaz-Gonzalez et al., 2016). The fluctuation of renewable distributed generation may cause instability in the grid, and since energy storage systems can operate as load or generator when it is in charging or discharging mode, it is able to balance the power in the microgrid and reduce the impact of any fluctuation, thereby significantly improving the stability of the microgrid (Gao, 2015). Some of the parameters for deciding the appropriate storage technologies to be used for specific applications are power rating, ramp rate, storage capacity, specific energy, energy density, round-trip efficiency, lifetime, site specificity, power cost, and energy cost.

Energy storage systems come in different forms, they can be mechanical, electrical, electrochemical, and thermal systems. Mechanical storage systems are pumped hydro, compressed air and flywheel, and electrochemical storage systems are secondary batteries, flow batteries, and fuel cell. Energy storage systems store off-peak power during light load demands and supply the stored energy to the grid during peak load demands. Emphasis is placed on pumped hydro and battery energy storage system in this study.

3.4.1. Battery Energy Storage System

Battery energy storage system has a high ramp rate, and can respond to grid demands almost immediately. Batteries convert electrical energy to potential chemical energy when charging, and release the electrical energy to the connected loads when discharging by converting their chemical energy back into electrical energy. The types of batteries that are used in different stationary and nonstationary fields of application are lead-acid, nickel-cadmium (Ni-Cd), sodium-sulfur, lithium-ion (Li-ion), and flow batteries (Diaz-Gonzalez et al., 2016). Battery size is a design variable, and is generally based on the desired autonomy period, depth of discharge (e.g., 50%), and derating for round-trip efficiency (e.g., 75%) (Foster et al., 2009)**.** Operating a BESS at a shallow depth of discharge (DoD) will increase the operational life of the battery. Lead-acid batteries have a poor cycle life of 200 – 1800 cycles depending on the depth of discharge and the operating temperature (Diaz-Gonzalez et al., 2016). Ni-Cd batteries present good characteristics with regard to cyclability (more than 3500 cycles, and up to 50000 cycles at 10% DoD), high ramp rates, and low maintenance, sodium-sulfur batteries have a high efficiency (85%), very low self-discharge rate, low maintenance, and almost 99% recyclability, while Li-ion batteries have fast charge and discharge capabilities, relatively high round-trip with efficiency of 78% (Diaz-Gonzalez et al., 2016).

3.4.2 Pumped Hydroelectric Storage

In a pumped hydroelectric storage system, excess energy during off-peak periods are used to pump water from the lower reservoir to the upper reservoir, and the water is later discharged from the upper reservoir to the lower reservoir through the reversible-pumped turbine during peak periods for meeting the peak load requirements. Its operating principle is based on managing the gravitational potential energy of water by pumping it from a lower reservoir to an upper reservoir while consuming power from the grid, or by releasing water from the upper reservoir to the lower reservoir when energy needs to be injected into the grid (Diaz-Gonzalez et al., 2016). The extent of generation depends on the topography of an area and its annual precipitation (Chowdhury et al., 2009). The construction of pumped hydroelectric system highly depends on the availability of a very hilly geographical environment with at least 100 meters between the upper and lower reservoirs (Diaz-Gonzalez et al., 2016). The energy stored in a pumped hydroelectric storage system is proportional to the volume of water in the upper reservoir and the height of the waterfall. Output power from the turbine can be increased by increasing the effective head and the water flow rate (Chowdhury et al., 2009**)**. The pumped hydroelectric storage turnaround efficiency is usually in the range of 70 – 85% (Ter-Gazarian, 2011). The energy stored in a pumped hydroelectric electric storage system is calculated as shown in (6).

$$E_{PHS} = \rho g H V \tag{6}$$

Where ρ is the density of water (equivalent to $1000\ kg/m^3$), g is the acceleration due to gravity, V is the volume of water stored in the upper reservoir, and E_{PHS} is the energy stored, in joules.

There are several lakes and dams in Nigeria that can be utilized for the purpose of constructing pumped hydroelectric storage systems. Some of the dams have been constructed for purposes such and irrigation, and for providing drinking water for the inhabitants of the regions. One of such dams is Dadin Kowa Dam, which is located in Gombe State, in the north-eastern part of Nigeria. The dam has a total capacity of 800 million m^3, with a surface area of 300 m^2. Another of these dams are Challawa Gorge Dam in Kano State which has a capacity of 930 million m^3, Tiga Dam, also in kano State with a capacity of 1874 million m^3, kafin Zaki Dam in Bauchi State with a capacity of 2700 million m^3, and Kiri Dam in Adamawa State with a capacity of 615 million m^3.

3.5. Renewable Energy Trends

Renewables are the second largest contributor to global electricity production as they account for 23.8% of world generation in 2016, after coal (39.2%), and ahead of gas (23.6%), nuclear (10.6%) and oil (3.8%) (IEA, 2018). In 2016, the world Total Primary Energy Supply (TPES) was 13761 Mtoe with 13.7% of it being from renewable energy sources (IEA, 2018). From the total renewable energy produced in 2016, 2.5% was from hydroelectric power systems, 9.5% was from biofuel and non-renewable wastes, while the remaining 1.6% was from the combination of solar, wind, geothermal, and tidal sources. In most of the developing countries, which are situated majorly in Africa, Asia, and South America, solid biofuels such as wood and charcoal are used for non-commercial purposes such as residential heating and cooking. In the last two decades, the installation of hydroelectric power systems is carried out more in non-OECD countries, and the reason is that most of the non-OECD countries are still developing and have not fully utilized their hydroelectric power generation potentials. The OECD countries, on the other hand, have almost fully utilized their hydroelectric power generation potentials, and are now more focused on developing their renewable energy generation capacities. Non-OECD countries are the principal renewable energy users of non-commercial solid biofuels, accounting for 72.3% of the world total renewable supply, while in 2016 the OECD countries accounted for 63.3% of world energy from solar, wind, tide, renewable municipal waste, biogases, and liquid biofuels (IEA, 2018).

In OECD countries, the total primary energy supply (TPES) from renewable sources increased from 272 Mtoe to 539 Mtoe between 1990 and 2017, an average annual growth of 2.6% (IEA, 2018). Renewable energy accounts for 95% of all new EU power installations in 2018; 19.8 GW of a total of 20.7 GW of new power capacity (Wind Europe, 2019). Policies and incentives by the government that support the installation and growth of renewable energy are some of the motivations for renewable energy implementations in OECD countries. At the end of 2016, approximately 1019.2 GW, or 34.6% of the total OECD generating capacity was from renewable energy and waste resources (IEA, 2018**)**. There are now 189 GW of installed wind power capacity in Europe with 170 GW onshore and 19 GW offshore. 68% of the total wind power in Europe is installed in just five countries, and they are Germany (59.3 GW), Spain (23.5 GW), the UK (12 GW), France (15.3 GW), and Italy (10 GW), with Sweden, Turkey, and Poland following with wind installation capacities of 7.4 GW, 7.4 GW, and 5.9 GW respectively (Wind Europe, 2019**)**.

Africa has about 6.1 GW of wind power capacity, with the notable wind farms situated in countries such as Morocco, Kenya, Egypt, Ethiopia, and South Africa. Zafarana wind farm in Egypt has the largest installed capacity of about 550 MW. Lake Turkana Wind Power (LTWP) is a wind farm in Kenya with a capacity of 310 MW comprising of 365 wind turbines, with each turbine having a capacity of 850 kW. LTWP represents about 17% of Kenya’s total installed capacity. Tarfaya wind farm in Morocco has 131 wind turbines with a total nominal capacity of 301.2 MW, with each turbine having a capacity of 2300 kW and a rotor diameter of 101 m. Adama II wind farm in Ethiopia has 102 turbines with a total nominal power of 153 MW with each turbine having a capacity of 1500 kW and 77.7 m rotor diameter. There are a number of wind farms in South Africa, 4and the biggest among them is Amakhala Emoyeni wind farm which has 56 wind turbines with a total nominal capacity of 134.4 MW, with each of the turbines having a capacity of 2400 kW.

3.6. Renewable Energy in Nigeria

Despite the enormous amount of renewable energy resources that are available in Nigeria, the country is still yet to take advantage of these free and clean sources for electricity generation. As can be seen in Fig. 1, the percentage of non-renewable sources in the energy mix for electricity generation is 86 percent of the total installed capacity, with only 14 percent being derived from hydroelectric power sources. Tables 8 and 9 show the wind and solar energy resources for different states in Nigeria, and they give an idea of how much of electricity can be generated by judiciously utilizing these resources. The proper utilization of these renewable resources will have a positive impact on the quality of life of the Nigerian populace by increasing the energy per capita and at the same time reducing the amount of CO_2 in the atmosphere.

A number of small off-grid renewable energy installations exist all around the country, they have sizes in the range of a few kilowatts and are used to power schools in remote areas, and healthcare centers. Among them are a 5 kW wind power installation for village electrification in Sayya Gidan Gada in Sokoto State, a 7.2 kWp PV village electrification project in Kwalkwalawa, Sokoto, and a 1000 liter solar water heating system in Usmanu Danfadiyo University Teaching Hospital, Sokoto. Also, there is a wind farm in Katsina State that has 37 turbines, having a total nominal capacity of 10.175 MW, with each turbine rated at 275 kW, a rotor diameter of 32 m, and a hub height of 55 m.

4. METHODOLOGY AND RESEARCH SCENARIOS

4.1.1. Methodology

This study focuses on the means of increasing the reliability and efficiency of the Nigerian electricity system without having to involve rigorous modifications of the transmission system. One of the aims of this research is designing a system that is capable of meeting the customers' electricity needs with minimal or no modifications of the transmission system, while also ensuring that the grid code requirements are not violated. This study is divided into four scenarios, with the aim of investigating the effects of the gradual load and generation increments on the operations of the grid. Nigeria's electrification rate is assumed to be 55.5 percent, and the availability of electricity is assumed to be averagely 15 hours per day. From the daily operational report of 28/01/2019, obtained from TCN, the average energy generated per hour was 4090.37 MWh/h, and the average energy sent out per hour was 4039.81 Mwh/h. This implies a generation system loss of about 1.082 percent. The transmission and distribution systems losses according to (PwC, 2016) are 7 percent and 12 percent respectively. The distribution system losses are not considered in the study, as the focus is only on the amount of power that is available to the DisCos from the transmission system. The total losses considered are those due to the generation system and the transmission system, which approximately amount to a total of about 8.149 percent. In scenario 1, the electrification rate is increased to 75 percent while still keeping the electricity availability at 15 hours per day. In scenario 2, the electrification rate is increased to 100 percent, with availability still at 15 hours per day. In scenario 3, the electrification rate is kept at 75 percent, and the number of hours of electricity availability per day is increased to 24 hours. In scenario 4, the electrification rate is 100 percent, and electricity availability is 24 hours per day. The grid is divided into ten regions, and the estimated load, with the amount of generation required for each region is shown in Table 9 below. The power sent over the three international lines is constant and is estimated to be 364.5 MW. The total load as indicated in Table 9 is the addition of the total local load demands and the power sent over the international lines.

Table 9. Load and Generation Requirements per Region

Region	Percentage of Load (%)	Base Load (MW)	Scenario 1 load (MW)	Scenario 2 Load (MW)	Scenario 3 Load (MW)	Scenario 4 Load (MW)
Abuja	15.11	512.71	692.85	923.81	1108.57	1478.09
Benin	7.06	239.38	323.49	431.32	517.58	690.11
Lagos	30.03	1018.67	1376.59	1835.45	2202.54	2936.72
Enugu	6.97	236.4	319.46	425.95	511.14	681.52
Ibadan	12.48	423.29	572.02	762.69	915.23	1220.30
Jos	5.59	189.59	256.20	341.61	409.93	546.57
Kaduna	5.88	199.32	269.35	359.14	430.96	574.62
Kano	4.89	166	224.33	299.10	358.92	478.56
Port Har.	8.67	294.2	397.57	530.09	636.11	848.15
Yola	3.33	112.97	152.66	203.55	244.26	325.68
	100.00	**3392.53**	**4584.52**	**6112.69**	**7335.23**	**9780.31**

Total Load	3757.03	4949.02	6477.19	7699.73	10144.81
Total Generation	4090.37	5352.314	7005.02	8327.18	10971.51
No. of Microgrids Installed	0	5	11	17	25

The power flow study of the grid was carried out using DigSILENT PowerFactory. The operation of the grid under the different load and generation conditions was observed. During the power flow study, Egbin power station was selected as the slack generator because of its position in the grid, and its capability to provide support to several load areas, and also because of its size as the generation station with the highest installed capacity. The number of microgrids required to meet the additional load requirements is given in Table 9 above. The regions that are the weakest in the grid; with low power factors and low voltages, are targeted for the installation of the microgrids. In scenario 1, the regions with no generation, which are Enugu, Jos, Kaduna, Kano, and Yola are provided with one microgrid each.

Modular microgrids with 250 MW generation capacity each are adopted in this study, with wind and solar energy harnessed as the sources of renewable energy. BESS is used for the storage of electricity on the grid. From Table 7, it can be observed that wind energy can be harnessed in almost all the regions in Nigeria. For solar energy, as can be seen in Table 7, only the areas with GHI of above 5 $kWh/m^2/day$ are considered for solar PV installations. For the regions with solar energy potentials, the modular microgrid will consist of the combination of solar PV and wind turbine installations, each sized at 125 MW, and also BESS and critical loads. The regions that are not considered for solar PV installations will only contain microgrids having wind turbines with generation capacities of 250 MW, BESS and critical loads. Due to the intermittent nature of renewable energy sources such as wind and solar, including storage systems in the design will help to smooth out the variations in the generated power. The battery smoothes out or reduces temporarily high voltages (transient voltages) that may occur in the PV electrical system (Foster et al., 2009). Storage systems also help to meet the difference in generation and load demands. For example, in the night, solar panels do not produce any energy from sunlight because they do not work in darkness, and wind turbines, on the other hand, can produce a varying amount of power throughout the day. Figure 9 below shows the connection of a wind turbine, solar PV, and BESS for providing support to the main grid.

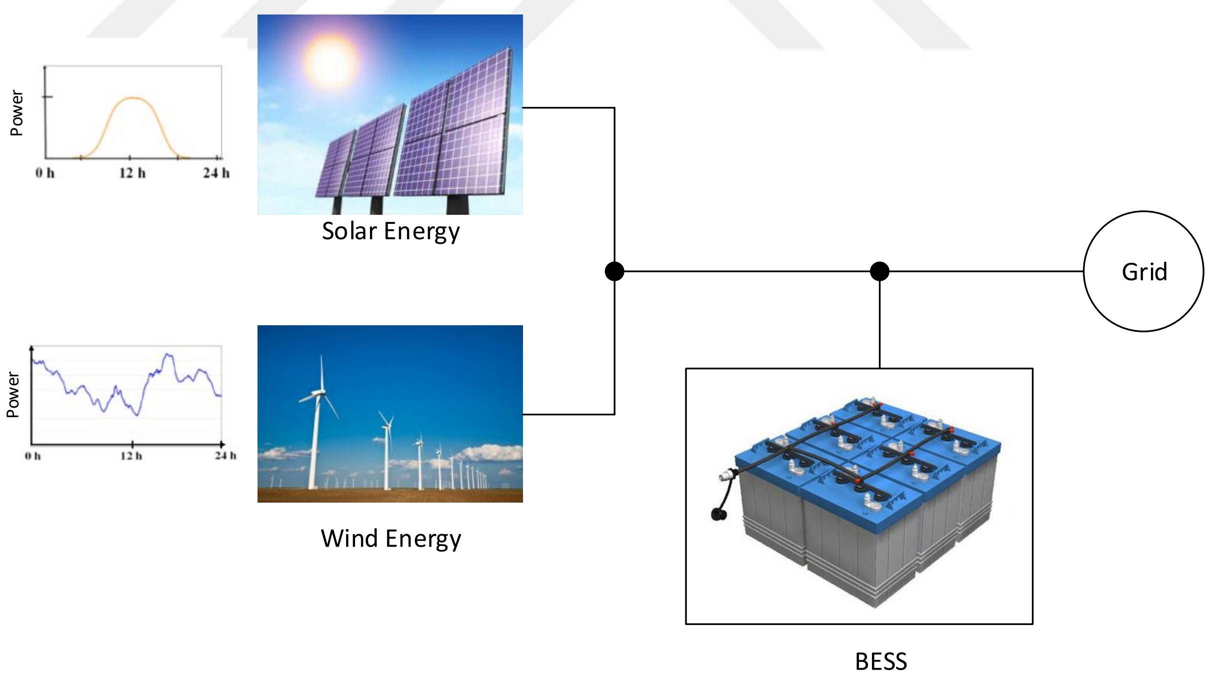


Fig. 9. Microsources and BESS

To even out the fluctuations in the power produced by both the solar PV and the wind turbine, an appropriately sized storage system is required. For BESS, during the periods of low energy demands, the excess power from the generators is used to charge the batteries, and the stored energy is released back to the system during the periods of peak load demands. Likewise in hydroelectric storage systems, during the periods of fewer load demands, excess power from the generators is used to pump water from a lower reservoir to an upper reservoir, and during peak load demands, the stored water in the upper reservoir is released to drive the pumped hydroelectric turbines to meet peak load demands.

4.2. BESS Sizing

Battery size is a design variable and is generally based on the desired autonomy period, depth of discharge (e.g. 50 %), and derating for round-trip efficiency (e.g. 50%) (Foster et al., 2009). A battery bank should be designed for 3 days of autonomy, not exceeding 45% depth of discharge (Foster et al., 2009). Assuming we are designing a storage system with a nominal voltage of 24 V and required to serve a critical load of 250 MW for an autonomy period of 3 days.

The proposed size of the critical load = 250 MW

The total energy required per day = 250 MW × 24 hours = 6,000 MWh/day

The battery size required for 3 days autonomous operation = 18,000 MWh of storage capacity

Assuming we use 12 V deep cycle batteries with a capacity of 100 Ah each, with expected efficiency of 75%, and 45% DoD.

The number of batteries in parallel = $\frac{18000\ MWh}{(45\%\ DoD \times 75\%\ efficiency \times 100\ Ah \times 24\ V)} = 22{,}222.22$ batteries.

The number of batteries in series = $\frac{24\ V\ BESS\ nominal\ voltage}{12\ V\ battery\ voltage} = 2$ batteries.

The total number of series-parallel batteries = 22,222.22 × 2 ≈ 44,444 series-parallel batteries.

4.3. Research Scenarios

The investigation of the grid's operations in this thesis is divided into four scenarios, with each scenario representing a different load and generation requirements. Due to the high frequency of power interruptions experienced by electricity consumers in Nigeria, and the low availability of electricity, there is a need for an urgent intervention that is focused on increasing the generation capacity as well as the reliability of the power system. Figure 10 is a graphical representation of the load and generation requirements for the different scenarios. Figure 11 shows the per-unit values of the voltages at different busbars.

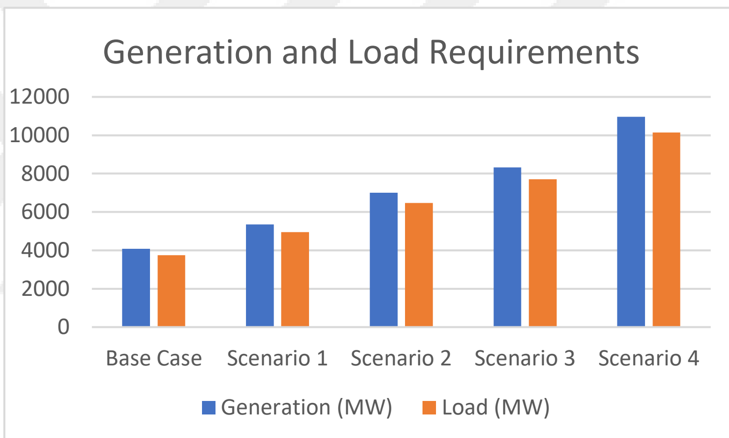
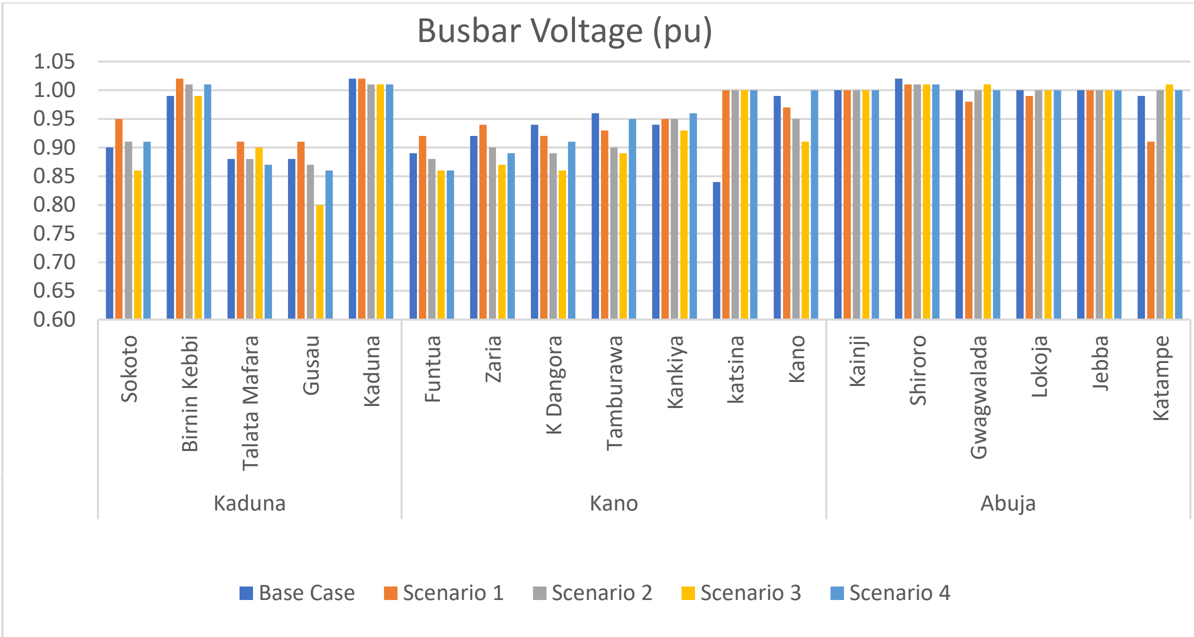
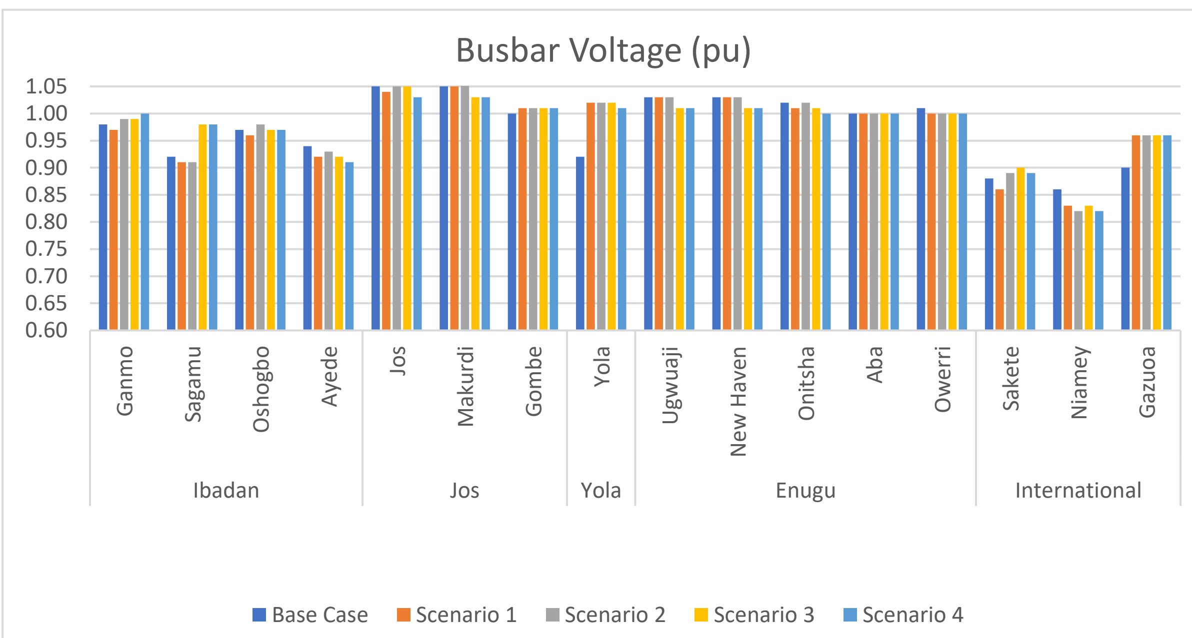


Fig. 10. Generation and load requirements



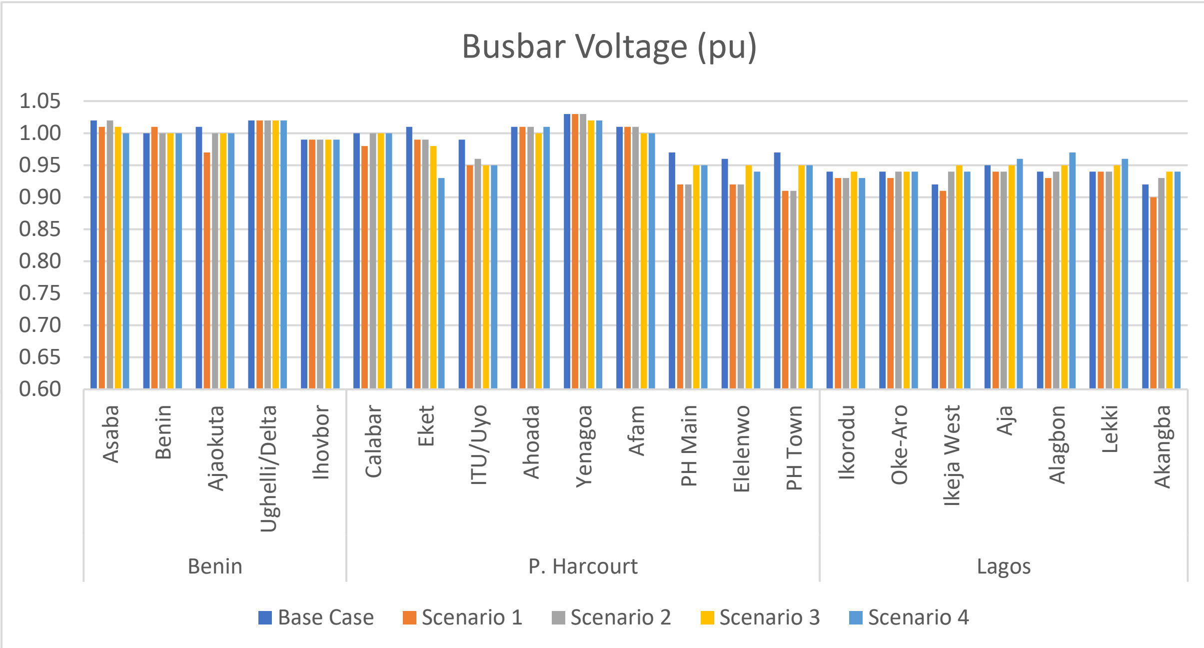
(a)

Fig. 11 (a) – (c). Busbar voltages in per unit



(b)

Fig. 11. continued



(c)

The base case load and generation values as shown in Fig. 10, give an idea of what the operational strength of the grid presently is. By decentralizing the generation system with distributed generators, the strength of the grid and its reliability can be improved without needing to do a lot of modifications to the transmission system. The per-unit values of the busbar voltages as shown in Fig. 11, summarizes the reactions of the different areas to load and generation increments. The range of permissible operational voltages on the grid is given in Table 2. The voltage profiles of Abuja, Yola, Enugu, and Benin are good. Kaduna and Kano have poor voltage profiles because of the low ratings of some of their transmission conductors which are unable to support large power flow. The voltage profile of Niamey is also poor, and that is because of its lengthy transmission conductor and lack of proximity to a generation station. The voltage in Jos is somewhat high, this would have been an advantage if the transmission system was not radial, as power could be easily wheeled to other areas where more power is needed. It can be seen in Fig. 10 that the load requirement for scenario 4 more than doubles that of the base case. Although the grid was able to operate under large load increments, a few of the conductors and transformers operated under critical conditions.

4.3.1. The Base Case

The grid operation of 28/01/2019 is used as the base case. For this day, the average energy generated per hour was 4090.37 MWh/h, and the average energy sent out per hour was 4039.81 MWh/h. The peak generation was 4490.8 MW, and the off-peak generation was 3621.7 MW. With a generation system loss of about 1.082 percent; which is obtained from the difference between the energy generated and the energy sent out, and with a transmission loss of about 7 percent, the total loss within the generation and transmission system is about 8.149 percent. Distribution loss is not considered in this study. The value of the average energy generated per hour is used to size the generation system. The load demand value is obtained from the average energy generated per hour after taking out the transmission and generation losses. In this scenario, the electrification rate is assumed to be 55.5 percent, and the electricity availability is assumed to be 15 hours per day.

The operation of the grid under the base case is somewhat satisfactory. Both the generation and the transmission system do not show a sign of overload. The voltage at Jos T.S. is high, and the conductor connecting Kainji G.S. to Kainji T.S. is slightly overloaded. Under this scenario, Enugu, Jos, Kaduna, Kano, and Yola do not have any form of generation. Although the grid seems to be operating fine, an attempt to increase the load demand might cause the system to be stressed and might result in grid collapse. The modeling diagram and the load flow analysis result for this scenario can be found below in Fig. 12 and 13 respectively.

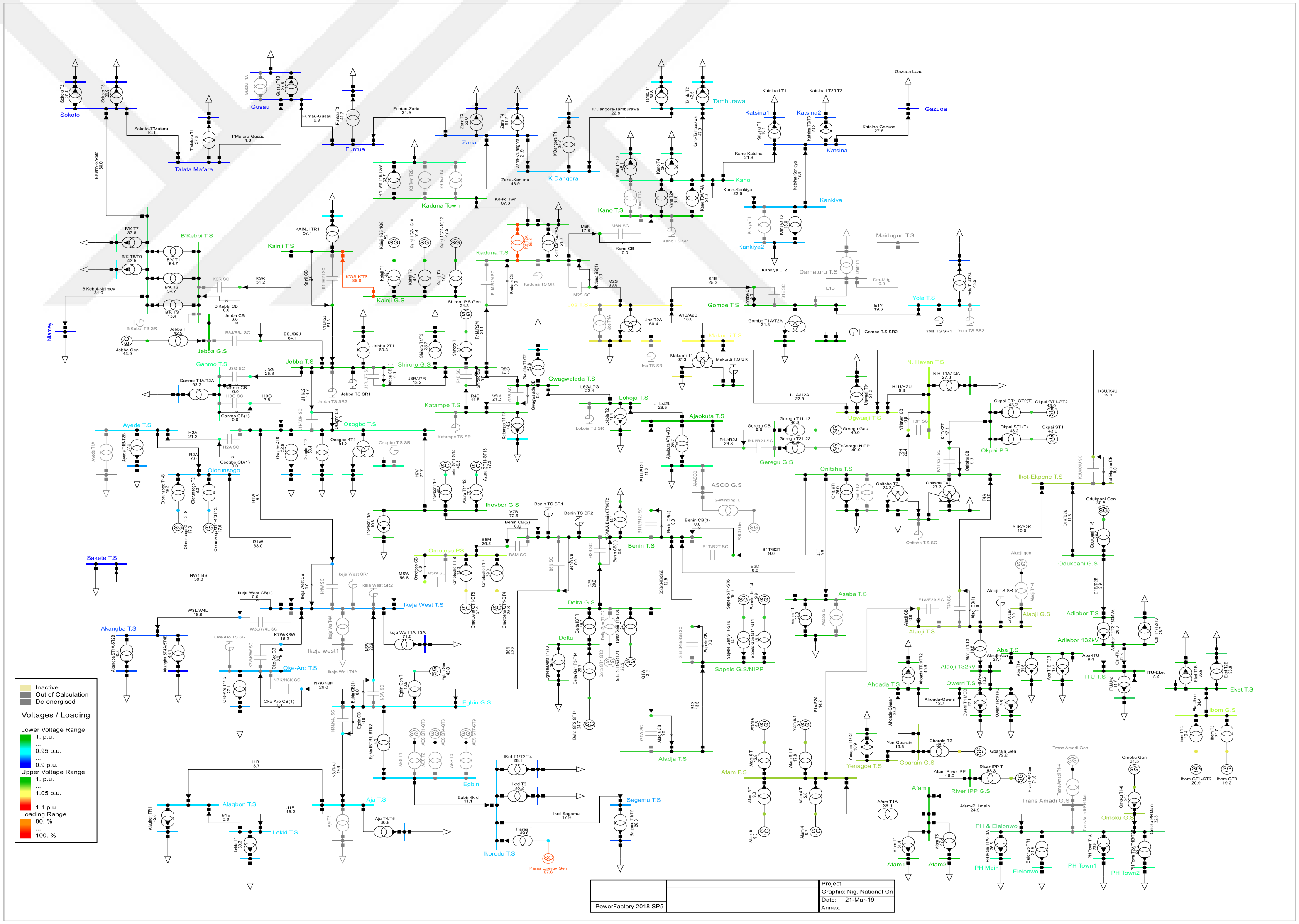


Fig. 12. Base case study diagram

```
-----------------------------------------------------------------------------------------------------------------------------------
|                 |                                                                |  DIgSILENT   | Project:                           |
|                 |                                                                | PowerFactory |------------------------------------
|                 |                                                                |   2018 SP5   | Date:  21-Mar-19                   |
-----------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                                              Grid Summary |
-----------------------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence          |   Automatic Model Adaptation for Convergence           No               |
|     Automatic tap adjustment of transformers       No  |   Max. Acceptable Load Flow Error for                                   |
|     Consider reactive power limits                 No  |      Nodes                                             1.00 kVA        |
|                                                        |      Model Equations                                   0.10 %          |
-----------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------
| Grid: Nig. National Grid   System Stage: Nig. National G | Study Case: Base Case Scenario       | Annex:                    / 1   |
-----------------------------------------------------------------------------------------------------------------------------------
| Grid: Nig. National Grid                                                                                                        |
|                                                                                                                                 |
| No. of Substations     0         No. of Busbars        160         No. of Terminals      73         No. of Lines          87     |
| No. of 2-w Trfs.       106       No. of 3-w Trfs.      6           No. of syn. Machines  31         No. of Microgrids     0      |
| No. of Loads           78        No. of Shunts/Filters 8           No. of SVS            0                                       |
|                                                                                                                                 |
| Generation            =    3854.98  MW          697.06   Mvar     3917.50  MVA                                                 |
| External Infeed       =       0.00  MW            0.00   Mvar        0.00  MVA                                                 |
| Inter Grid Flow       =       0.00  MW            0.00   Mvar                                                                  |
| Load P(U)             =    3757.03  MW         2574.64   Mvar     4554.56  MVA                                                 |
| Load P(Un)            =    3757.03  MW         2574.64   Mvar     4554.56  MVA                                                 |
| Load P(Un-U)          =       0.00  MW            0.00   Mvar                                                                  |
| Motor Load            =       0.00  MW            0.00   Mvar        0.00  MVA                                                 |
| Grid Losses           =      97.95  MW        -2330.93   Mvar                                                                  |
| Line Charging         =                       -3211.66   Mvar                                                                  |
| Compensation ind.     =                         453.35   Mvar                                                                  |
| Compensation cap.     =                           0.00   Mvar                                                                  |
|                                                                                                                                 |
| Installed Capacity    =   12635.71  MW                                                                                          |
| Spinning Reserve      =     295.00  MW                                                                                          |
|                                                                                                                                 |
| Total Power Factor:                                                                                                             |
|   Generation          =          0.98  [-]                                                                                      |
|   Load/Motor          =   0.82 / 0.00  [-]                                                                                      |
|---------------------------------------------------------------------------------------------------------------------------------|
```

Fig. 13. Base case load flow analysis result

4.3.2. Scenario One

In this scenario, the electrification rate is increased from 55.5 percent to 75 percent while still keeping the electricity availability at 15 hours per day. The aim is to achieve a load increment that corresponds to 75 percent electrification rate without having to modify the transmission system. Five microgrids with microsources sized at 250 MW each are connected to the five areas that do not have any generation. The total load for this scenario is 4949.02 MW. While assuming that the total generation and transmission losses are 8.149 percent, a power generation of 5352.314 MW will be required to meet this load demand. It is assumed that the load increment is uniform across all regions. The positions of the microgrids can be found in the modeling diagram in Fig. 14. Also, the load flow study result can be found in Fig. 15.

Kaduna-Katsina, Katsina-Kankiya, and Kano-Kankiya transmission lines, which are in the Kaduna region are overloaded. The transmission system in Kano and Kaduna are very weak and radial and are easily overloaded. There is a need to strengthen the transmission conductors in these regions to improve the overall grid reliability. The transformer in Jos T.S. and the conductor connecting Kainji T.S. to Kainji G.S. are overloaded. Transforming the grid from a radial system to a mesh system will increase the reliability and resilience of the entire power system.

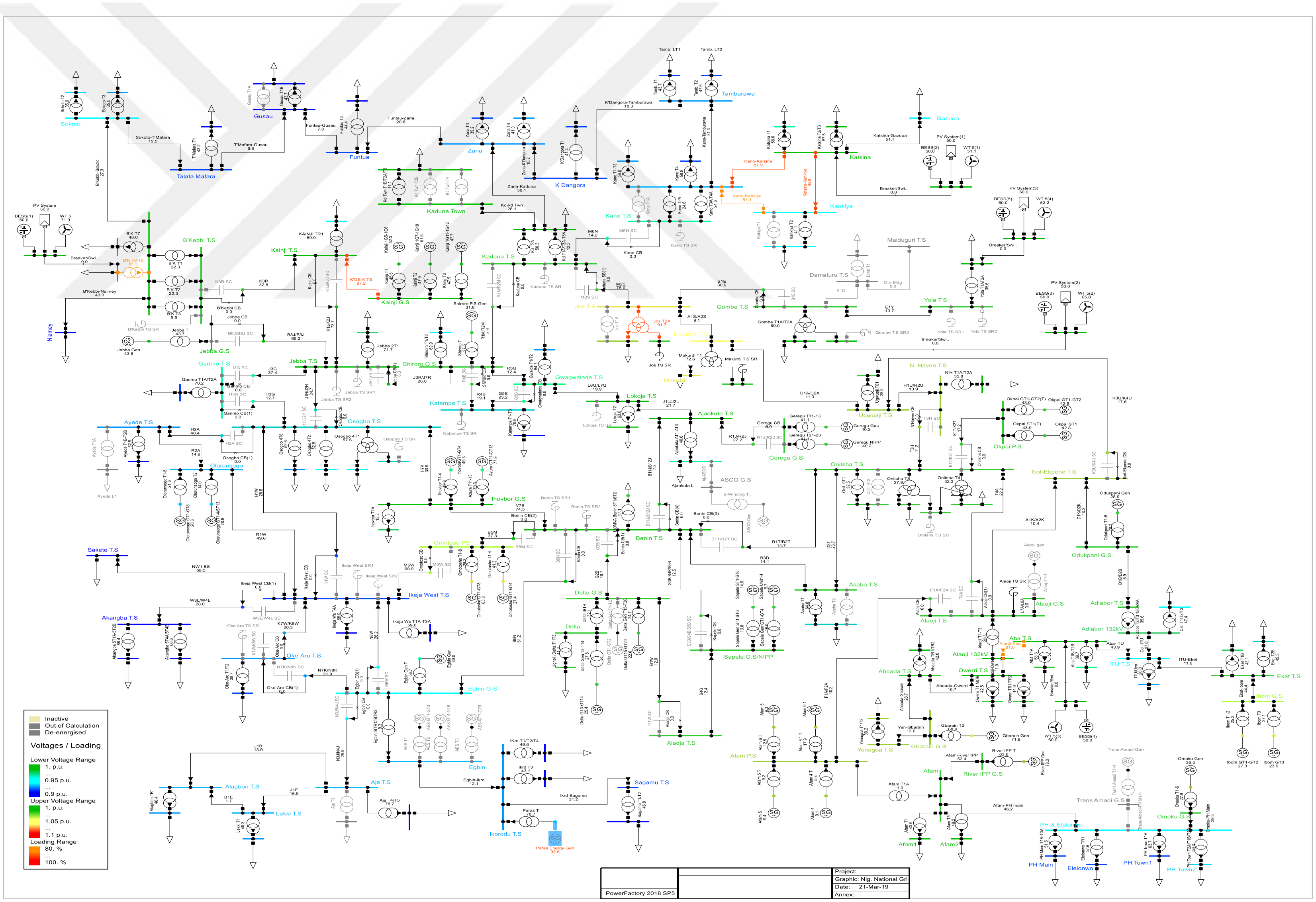


Fig. 14. Scenario 1 modeling diagram

```
----------------------------------------------------------------------------------------------------------------------------------
|                 |                                                                          |   DIgSILENT   | Project:          |
|                 |                                                                          | PowerFactory  |-------------------------------
|                 |                                                                          |    2018 SP5   | Date:  11-Mar-19  |
----------------------------------------------------------------------------------------------------------------------------------
----------------------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                                          Grid Summary |
----------------------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence            |   Automatic Model Adaptation for Convergence           No          |
|     Automatic tap adjustment of transformers        No   |   Max. Acceptable Load Flow Error for                              |
|     Consider reactive power limits                  No   |      Nodes                                            1.00 kVA    |
|                                                          |      Model Equations                                  0.10 %      |
----------------------------------------------------------------------------------------------------------------------------------
----------------------------------------------------------------------------------------------------------------------------------
| Grid: Nig. National Grid     System Stage: Nig. National G | Study Case: Scenario 1               | Annex:                / 1  |
----------------------------------------------------------------------------------------------------------------------------------
| Grid: Nig. National Grid                                                                                                     |
|                                                                                                                                |
| No. of Substations     0         No. of Busbars        160        No. of Terminals     73         No. of Lines          87   |
| No. of 2-w Trfs.       107       No. of 3-w Trfs.      6          No. of syn. Machines 31         No. of Microgrids     5    |
| No. of Loads           77        No. of Shunts/Filters 2          No. of SVS           0                                     |
|                                                                                                                                |
| Generation          =    5108.96  MW        1522.01  Mvar     5330.85  MVA                                                  |
| External Infeed     =       0.00  MW           0.00  Mvar        0.00  MVA                                                  |
| Inter Grid Flow     =       0.00  MW           0.00  Mvar                                                                   |
| Load P(U)           =    4949.02  MW        3408.34  Mvar     6009.12  MVA                                                  |
| Load P(Un)          =    4949.02  MW        3408.34  Mvar     6009.12  MVA                                                  |
| Load P(Un-U)        =       0.00  MW           0.00  Mvar                                                                   |
| Motor Load          =       0.00  MW           0.00  Mvar        0.00  MVA                                                  |
| Grid Losses         =     159.94  MW       -1964.43  Mvar                                                                   |
| Line Charging       =                        -3235.88  Mvar                                                                   |
| Compensation ind.   =                           78.11  Mvar                                                                   |
| Compensation cap.   =                            0.00  Mvar                                                                   |
|                                                                                                                                |
| Installed Capacity  =   13885.71  MW                                                                                         |
| Spinning Reserve    =     295.00  MW                                                                                         |
|                                                                                                                                |
| Total Power Factor:                                                                                                          |
|   Generation        =         0.96  [-]                                                                                      |
|   Load/Motor        =  0.82 / 0.00  [-]                                                                                      |
|--------------------------------------------------------------------------------------------------------------------------------|
```

Fig. 15. Scenario 1 load flow analysis result

4.3.3. Scenario Two

In scenario 2, the generation is 7005.02 MW, and the load demand is 6477.19 MW. Eleven microgrids are installed to provide support to the main grid. In this scenario, the electrification rate is increased to 100 percent while the availability of electricity per day is 15 hours. It is assumed that the loads are increased uniformly across all regions. The modeling diagram and the load flow analysis result can be found in Fig. 16 and 17 respectively.

The grid operated fine with a few of the grid components operating in critical conditions. The conductor connecting kainji G.S. to Kainji T.S. is overloaded. The weak transmission strength in the Kaduna region prevents the increment of load in Sokoto, Talata Mafara, and Gusau. In Kano, the Katsina-Kankiya line is overloaded, and some of the transformers in Katsina and Tamburawa are operating under critical conditions. The voltages in Jos T.S. and Makurdi T.S. are high, and their transformers are overloaded. There is a serious need to mesh the transmission system to allow power to flow from places with excess power than required, to places with power deficiencies. Also, increasing the power ratings of the transformers in Kano and Kaduna regions to accommodate higher load demands is necessary.

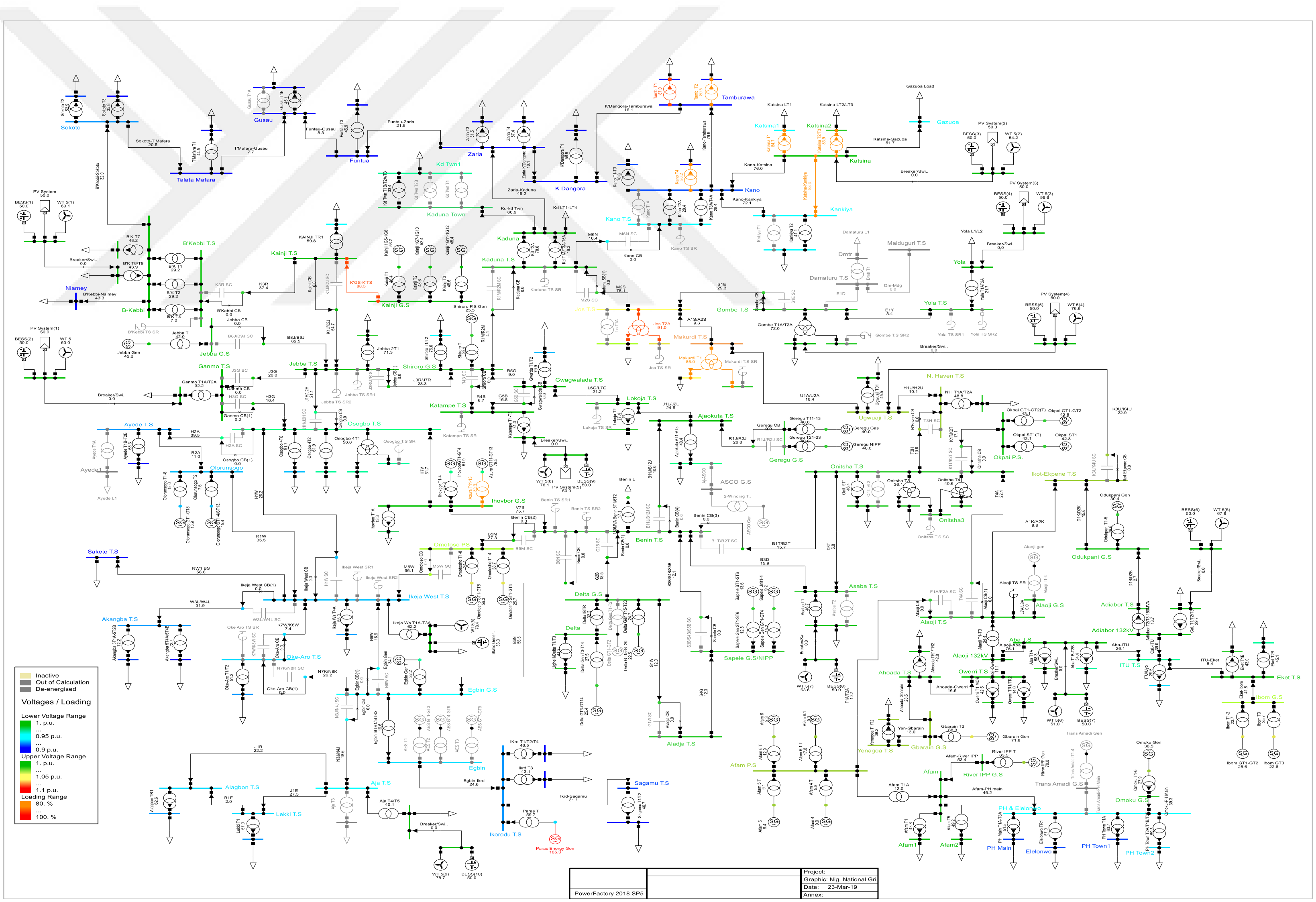


Fig. 16. Scenario 2 modeling diagram

```
-------------------------------------------------------------------------------------------------------------------
|              |                                                            |  DIgSILENT   | Project:              |
|              |                                                            | PowerFactory |---------------------------
|              |                                                            |   2018 SP5   | Date:  11-Mar-19      |
-------------------------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                              Grid Summary |
-------------------------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence            |   Automatic Model Adaptation for Convergence        No     |
|    Automatic tap adjustment of transformers        No   |   Max. Acceptable Load Flow Error for                      |
|    Consider reactive power limits                  No   |      Nodes                                        1.00 kVA |
|                                                         |      Model Equations                              0.10 %   |
-------------------------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------------------------
| Grid: Nig. National Grid   System Stage: Nig. National G | Study Case: Scenario 2          | Annex:          / 1 |
-------------------------------------------------------------------------------------------------------------------
| Grid: Nig. National Grid                                                                                         |
|                                                                                                                  |
| No. of Substations    0        No. of Busbars      160      No. of Terminals     73       No. of Lines        87 |
| No. of 2-w Trfs.      107      No. of 3-w Trfs.    6        No. of syn. Machines 31       No. of Microgrids   11 |
| No. of Loads          77       No. of Shunts/Filters 2      No. of SVS           0                                 |
|                                                                                                                  |
| Generation          =    6643.92  MW        2536.86  Mvar     7111.78  MVA                                       |
| External Infeed     =       0.00  MW           0.00  Mvar        0.00  MVA                                       |
| Inter Grid Flow     =       0.00  MW           0.00  Mvar                                                        |
| Load P(U)           =    6477.19  MW        4450.53  Mvar     7858.83  MVA                                       |
| Load P(Un)          =    6477.19  MW        4450.53  Mvar     7858.83  MVA                                       |
| Load P(Un-U)        =       0.00  MW          -0.00  Mvar                                                        |
| Motor Load          =       0.00  MW           0.00  Mvar        0.00  MVA                                       |
| Grid Losses         =     166.74  MW       -1991.56  Mvar                                                        |
| Line Charging       =                      -3224.73  Mvar                                                        |
| Compensation ind.   =                         77.90  Mvar                                                        |
| Compensation cap.   =                          0.00  Mvar                                                        |
|                                                                                                                  |
| Installed Capacity  =   15385.71  MW                                                                             |
| Spinning Reserve    =     295.00  MW                                                                             |
|                                                                                                                  |
| Total Power Factor:                                                                                              |
|   Generation        =         0.93  [-]                                                                          |
|   Load/Motor        =  0.82 / 0.00  [-]                                                                          |
|------------------------------------------------------------------------------------------------------------------|
```

Fig. 17. Scenario 2 load flow analysis result

4.3.4. Scenario Three

In scenario 3, seventeen microgrids are connected to the main grid to meet the load requirements for when the electrification rate is 75 percent, and the availability of electricity is 24 hours per day. The generation required to meet a load demand of 7699.73 MW is 8327.18 MW. The load is shared across all the ten areas according to the load percentages given in Table 9. Only the load consumed on the international lines have been left constant across all scenarios. The modeling diagram and the load flow analysis result for this scenario can be found in Fig. 18 and 19 respectively.

Although the grid was able to operate under this load condition, a few of the transformers and transmission lines are operating under critical conditions. Transformers in Zaria, Kaduna T.S., Katsina, and Kankiya, with Kano-Tamburawa and Katsina-Kankiya conductors, are operating under critical conditions. The conductors connecting Kainji T.S. to Kainji G.S., and Jos T.S. to Kaduna T.S. are also operating under critical conditions. The T1A transformer in Afam P.S. is operating under a critical condition with increased load.

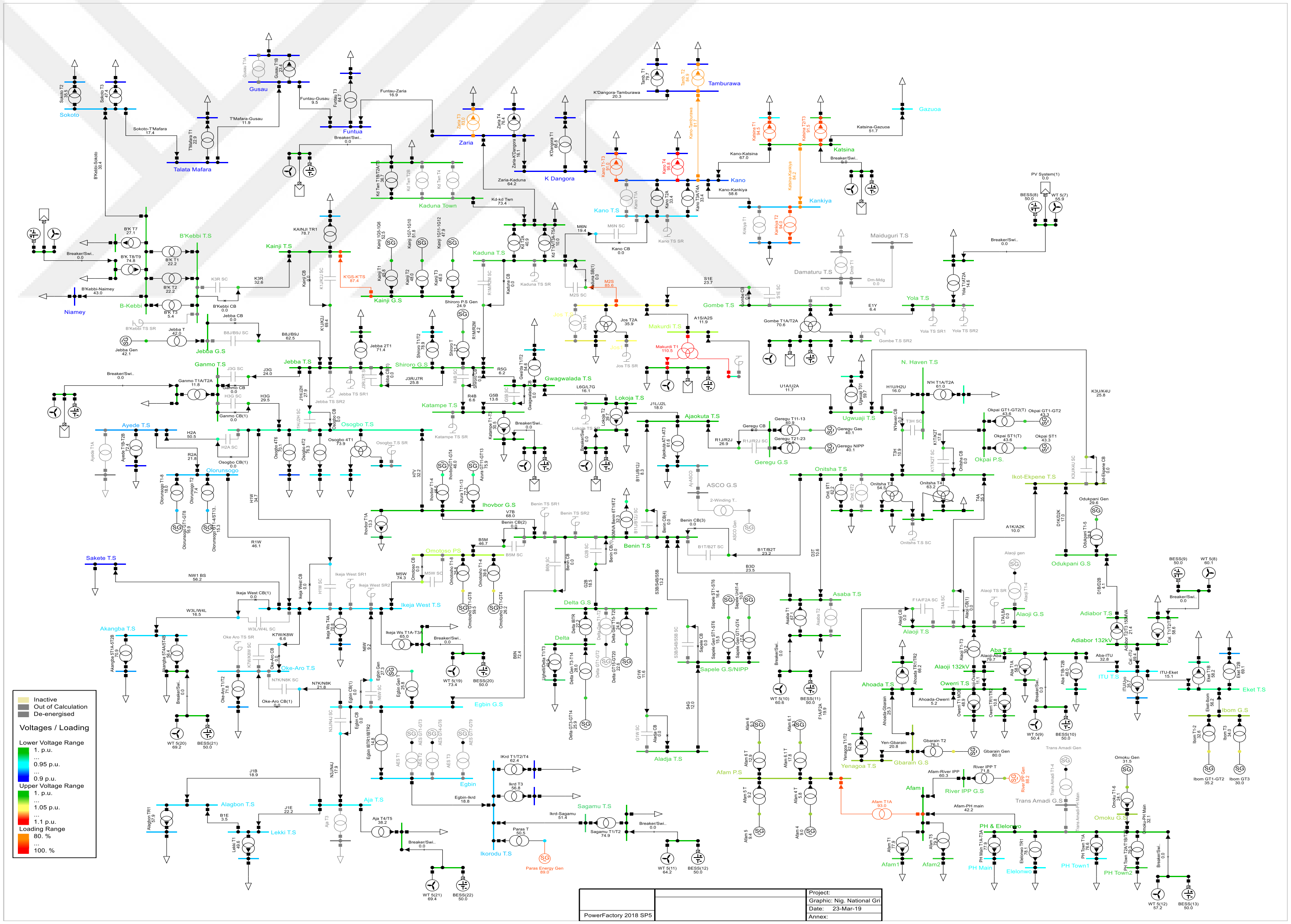


Fig. 18. Scenarios 3 modeling diagram

```
-----------------------------------------------------------------------------------------------------------------------------
|                |                                                               |  DIgSILENT  | Project:                      |
|                |                                                               | PowerFactory |-------------------------------
|                |                                                               |  2018 SP5   | Date:  10-Mar-19               |
-----------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                                         Grid Summary |
-----------------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence            |   Automatic Model Adaptation for Convergence          No        |
|     Automatic tap adjustment of transformers        No   |   Max. Acceptable Load Flow Error for                            |
|     Consider reactive power limits                  No   |      Nodes                                          1.00 kVA  |
|                                                          |      Model Equations                                0.10 %    |
-----------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------
| Grid: Nig. National Grid   System Stage: Nig. National   | Study Case: Scenario 3             | Annex:                / 1  |
-----------------------------------------------------------------------------------------------------------------------------
| Grid: Nig. National Grid                                                                                                   |
|                                                                                                                            |
| No. of Substations     0         No. of Busbars       160      No. of Terminals     73        No. of Lines          87      |
| No. of 2-w Trfs.       107       No. of 3-w Trfs.     6        No. of syn. Machines 31        No. of Microgrids     17      |
| No. of Loads           77        No. of Shunts/Filters 2       No. of SVS           0                                      |
|                                                                                                                            |
| Generation           =    7890.63  MW        3628.40   Mvar     8684.89  MVA                                              |
| External Infeed      =       0.00  MW           0.00   Mvar        0.00  MVA                                              |
| Inter Grid Flow      =       0.00  MW           0.00   Mvar                                                               |
| Load P(U)            =    7698.01  MW        5271.94   Mvar     9330.21  MVA                                              |
| Load P(Un)           =    7698.01  MW        5271.94   Mvar     9330.21  MVA                                              |
| Load P(Un-U)         =      -0.00  MW          -0.00   Mvar                                                               |
| Motor Load           =       0.00  MW           0.00   Mvar        0.00  MVA                                              |
| Grid Losses          =     192.62  MW       -1721.07   Mvar                                                               |
| Line Charging        =                      -3197.34   Mvar                                                               |
| Compensation ind.    =                         77.53   Mvar                                                               |
| Compensation cap.    =                          0.00   Mvar                                                               |
|                                                                                                                            |
| Installed Capacity   =   16885.71  MW                                                                                     |
| Spinning Reserve     =     295.00  MW                                                                                     |
|                                                                                                                            |
| Total Power Factor:                                                                                                        |
|   Generation         =         0.91  [-]                                                                                  |
|   Load/Motor         =  0.83 / 0.00  [-]                                                                                  |
|----------------------------------------------------------------------------------------------------------------------------|
```

Fig. 19. Scenario 3 load flow analysis result

4.3.5. Scenario Four

The load requirement for scenario 4 is 10,144.81 MW, and the generation requirement is 10971.51 MW. In this scenario, the electrification rate is increased to 100 percent, and the availability of electricity is increased to 24 hours per day. The amount of load required for this scenario is 288 percent of the base load. It is expected that the grid will support this load demand without the need for serious transmission system modifications. Twenty-five microgrids will be connected to different areas of the grid to provide support to the grid. The modeling diagram for this scenario and the load flow analysis result are shown in Fig. 20 and 21 respectively.

A lot of the components on the grid are operating under critical conditions in meeting the load and generation requirements needed to connect all customers to the grid and providing them with uninterrupted electricity. A few upgrades and reinforcements of the grid components will be needed to ensure that the grid effectively meets this load and generation requirements. Jos T.S. and Makurdi T.S. transformers are overloaded due to low load demands. With an appropriately sized storage system, the excess power from these transmission substations can be effectively utilized. Also, there is a need to connect the areas with excess power generation to areas that have lower generation capacities than load demand. Kano-Katsina, Kano-Kankiya, Katsina-Kankiya, and Kano-Tamburawa transmission conductors are operating under critical conditions. In Lagos, the transformers in Alagbon, Lekki, Oke-Aro, and Ikeja West are operating under critical conditions. In Port Harcourt, the transformers in Afam, PH Main T.S., PH Town, and Elelonwo are operating under critical conditions. The conductor connecting Kainji T.S. to Kainji G.S. is also operating under critical condition.

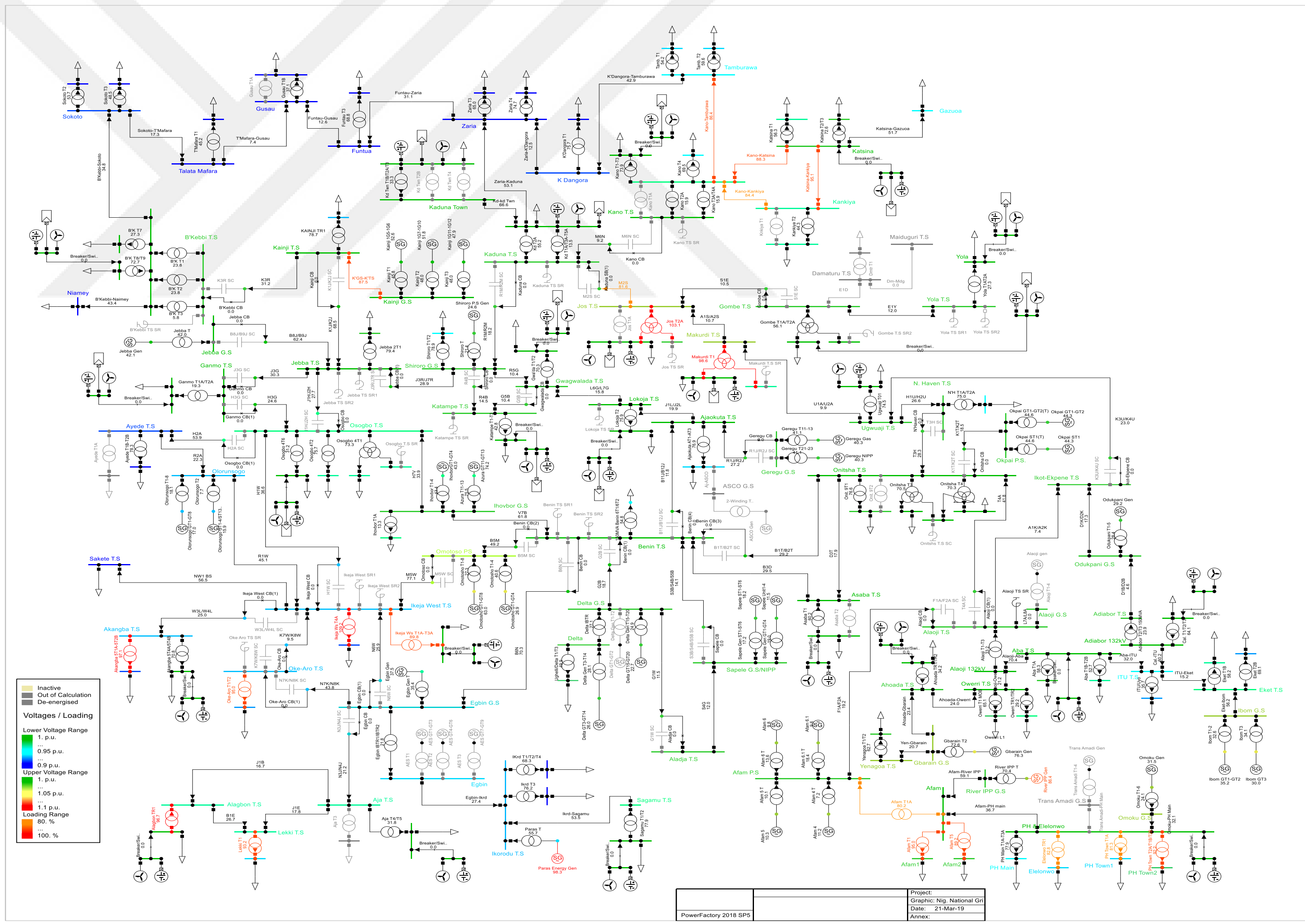


Fig. 20. Scenario 4 modeling diagram

```
-----------------------------------------------------------------------------------------------------------------------------------
|                |                                                                     |  DIgSILENT   | Project:                  |
|                |                                                                     | PowerFactory |---------------------------------
|                |                                                                     |   2018 SP5   | Date:  10-Mar-19          |
-----------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                                           Grid Summary |
-----------------------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence                | Automatic Model Adaptation for Convergence            No       |
|     Automatic tap adjustment of transformers        No       | Max. Acceptable Load Flow Error for                            |
|     Consider reactive power limits                  No       |    Nodes                                              1.00 kVA |
|                                                              |    Model Equations                                    0.10 %   |
-----------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------
| Grid: Nig. National Grid   System Stage: Nig. National G | Study Case: Scenario 4               | Annex:                 / 1  |
-----------------------------------------------------------------------------------------------------------------------------------
| Grid: Nig. National Grid                                                                                                      |
|                                                                                                                               |
| No. of Substations     0          No. of Busbars       160        No. of Terminals      73         No. of Lines          87    |
| No. of 2-w Trfs.       107        No. of 3-w Trfs.     6          No. of syn. Machines  31         No. of Microgrids     25    |
| No. of Loads           77         No. of Shunts/Filters 2         No. of SVS            0                                      |
|                                                                                                                               |
| Generation            =   10363.07  MW          5617.86  Mvar    11787.86  MVA                                               |
| External Infeed       =       0.00  MW             0.00  Mvar        0.00  MVA                                               |
| Inter Grid Flow       =       0.00  MW             0.00  Mvar                                                                 |
| Load P(U)             =   10144.82  MW          6950.33  Mvar    12297.34  MVA                                               |
| Load P(Un)            =   10144.82  MW          6950.33  Mvar    12297.34  MVA                                               |
| Load P(Un-U)          =       0.00  MW            -0.00  Mvar                                                                 |
| Motor Load            =       0.00  MW             0.00  Mvar        0.00  MVA                                               |
| Grid Losses           =     218.25  MW         -1409.87  Mvar                                                                 |
| Line Charging         =                         -3188.86  Mvar                                                                 |
| Compensation ind.     =                            77.40  Mvar                                                                 |
| Compensation cap.     =                             0.00  Mvar                                                                 |
|                                                                                                                               |
| Installed Capacity    =   18885.71  MW                                                                                        |
| Spinning Reserve      =     295.00  MW                                                                                        |
|                                                                                                                               |
| Total Power Factor:                                                                                                           |
|   Generation          =         0.88  [-]                                                                                     |
|   Load/Motor          =  0.82 / 0.00  [-]                                                                                     |
|-------------------------------------------------------------------------------------------------------------------------------|
```

Fig. 21. Scenario 4 load flow analysis result

Table 10. Summary of Grid Study

	Base Case	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Electrification Rate (%)	55.5	75	100	75	100
Electricity Availability (Hours/day)	15	15	15	24	24
Power from Solar Panel (MW)	0	500	750	1125	1750
Power from Wind Turbine (MW)	0	750	2000	3125	4500

Table 11. Summary of Load Flow Analysis Results

	Generation				Load				Grid Losses	
	R (MW)	Q (Mvar)	S (MVA)	PF	R (MW)	Q (Mvar)	S (MVA)	PF	R (MW)	Q (Mvar)
Base Case	3854.98	697.06	3917.5	0.98	3757.03	2574.64	4554.56	0.82	97.95	-2330.93
Scenario 1	5108.96	1522.01	5330.85	0.96	4949.02	3408.34	6009.12	0.82	159.94	-1964.43
Scenario 2	6643.92	2536.86	7111.78	0.93	6477.19	4450.53	7858.83	0.82	166.74	-1991.56
Scenario 3	7890.63	3628.4	8684.89	0.91	7698.01	5271.94	9330.21	0.83	192.62	-1721.07
Scenario 4	10363.07	5617.86	11787.86	0.88	10144.82	6950.33	12297.34	0.82	218.25	-1409.87

Tables 10 and 11 above are the summaries of the grid study and the load flow analysis results respectively. The electrification rate, electricity availability and the amount of power required from both solar PV and wind turbines to meet the load and generation requirements for each of the proposed scenarios are given in Table 10. In Table 11, the generation, load and grid losses values obtained from load flow analysis are given. Active power, reactive power, and apparent power for both the generation and the load are given together with their power factors.

4.4. DigSILENT PowerFactory

DigSILENT PowerFactory 2018 SP5 was used for the simulation of the electricity grid in this study. PowerFactory is a software developed by DigSILENT GmbH for carrying out electric power system simulations; transmission, distribution, and generation system studies, and for the simulation of grid integration of renewable energy sources. The software can be used for numerous analyses in the field of power systems, among which are load flow analysis, contingency analysis, quasi-dynamic simulation, cable analysis, power quality and harmonics studies, optimal power flow studies, with probability and reliability analyses among others.

PowerFactory provides all the necessary functionality to conduct complex studies for the integration of renewable generation into distribution, transmission and industrial networks, which nowadays is one of the key issues in network planning and analysis (PowerFactory, n.d.). It covers the full range of functionality from standard features to highly sophisticated and advanced applications including wind power, distributed generation, real-time simulation and performance monitoring for system testing and supervision (PowerFactory, n.d.).

5. RECOMMENDATION AND CONCLUSION

5.1. Recommendation

In Abuja, the capacity of the conductor connecting Kainji T.S. to Kainji G.S. needs to be increased. The transformers in the Abuja region seem to be adapting well to the load changes, but improving their power ratings will be advantageous for the purpose of future load increments. In Kaduna region, the power ratings of the transformers in Sokoto, Talata Mafara, and Gusau are small, and inadequate for large load demands. Increasing the power ratings of these transformers, and also improving the transmission strength within the region is recommended. The majority of the transformers in the Kano region also have low power ratings. Increasing their power ratings is highly necessary for meeting future load demands.

In Enugu, the grid components seem to be operating fine, however, the increment of the ratings of the transformers is recommended for meeting future load demands. In Jos T.S., Makurdi T.S., and Gombe T.S., the load demands are usually not very high, resulting in high voltages at the transmission substations busbars. Creating connections from these substations to other areas where power is deficient will be of great benefit. Also, increasing the ratings of the transformers in this region to meet future load demands is recommended. The conditions of operation of the grid components in Benin is satisfactory, however, for the purpose of future load increments, the upgrade of some of the transformers and conductors should be considered.

During large load demands, most of the transformers in the Port Harcourt region operated under critical conditions. Increasing the ratings of these transformers is necessary for meeting large load requirements. Yola T.S. is connected only to Gombe T.S. with a single circuit conductor. To increase the reliability in this area, reinforcing the connection to Gombe T.S., and also creating connection points to neighboring transmission substations is recommended. For meeting future load requirements, increasing the power ratings of the transformers in Osogbo T.S. is necessary. During the power flow study for scenario 4, the transformers in Ikeja West T.S., Akangba T.S., Alagbon T.S., and Lekki T.S. were all operating under critical conditions.

They were all loaded close to their full power ratings. Therefore, increasing their power ratings is urgently recommended.

The reactive power on the grid is very high, and the power factor is very low, thereby urgently requiring reactive power compensation on the grid. Installing reactive power compensators at the appropriate locations to increase the power factor on the grid is highly necessary.

5.2. Conclusion

The aim of this study is to investigate how the Nigerian electricity grid would operate under increased load and generation conditions without having to modify the transmission system. The result of this study shows that the reliability and resilience of Nigeria's national grid can be improved with renewable energy-based microgrids, and because the proposed primary source of energy is sustainable and clean, the impact of global warming can be greatly reduced. With a low generation capacity and a weak transmission system, increasing the electrification rate to 100 percent, and electricity availability to 24 hours per day can only be achieved by installing distributed generators and storage systems in the critical regions where power is deficient. Installing the distributed generators and storage systems close to the critical loads will improve the reliability and the efficiency of Nigeria's electricity system. Due to the effects of greenhouse gases on our planet, which has prompted efforts to reduce the combustion of fossil fuels, utilizing renewable energy sources such as wind and solar for power generation can help to mitigate the effects of global warming. Also, the proposed energy storage systems in this study which are BESS and pumped hydroelectric storage will improve the efficiency of the power system by helping to balance the difference between load demand and energy supply when there is an insufficient generation or during power interruptions. During the four scenarios created to investigate the grid's operational strength when load and generation capacities are increased, it can be concluded that the grid operated satisfactorily with a few of the grid components operating under critical conditions without violating the grid code requirements. With this, the ability of microgrids to support the operations of the grid by improving resilience and reliability is verified. The results of this study show that despite the low power wheeling capacity of Nigeria's transmission system, it is possible to provide uninterrupted electricity to all the inhabitants of Nigeria by using renewable energy-based generators and storage that are connected close to the critical loads.

6. REFERENCES

Ahmed, A., & Gidado, K., 2008. Evaluating the potential of renewable energy technologies for buildings in Nigeria. In: Dainty, A (Ed) Procs 24th Annual ARCON Conference, 1 - 3 September 2008, Cardiff, UK, Association of Researchers in Construction Management, 1175 - 1182.

Airoboman, A. E., Ogujor, E. A., & Okakwu, I. K., 2017. Reliability analysis of power system network: a case study of transmission company of Nigeria, Benin City. IEEE PES-IAS Power Africa, 99-104.

Ajao, K. R., Ajimotokan, H. A., Popoola, O. T., & Akande, H. F., 2009. Electric energy supply in Nigeria, decentralized energy approach. Cogeneration and Distributed Generation Journal, 24(4), 34-50.

Akpan, U. S., Isihak, S. R., & Udoakah, Y. N., 2013. Electricity access in Nigeria: viability of off-grid photovoltaic system. IEEE.

Akpojedje, F. O., Onogbotsere, M. E., Mormah, E. C., & Onogbotsere, P. E., 2016. A comprehensive review of Nigeria electric power transmission issues and rural electrification challenges, *31*(1), 1–9.

Akuru, U. B., Ogbonnaya, I. O., & Chikuni, E., n.d. Impact of renewable energy deployment on climate change in Nigeria.

Akuru, U. B., & Okoro, O. I., 2010. Renewable energy investment in Nigeria: a review of the renewable energy master plan. IEEE International Energy Conference, 166–171.

Amadi, H. N., 2017. Distributed generation in Nigeria's post-privatized power sector - challenges and prospects. International Journal of Engineering Research and Application (IJERA), 7(7), 54 - 70. https://doi.org/10.9790/9622-0707075470

Chowdhury, S., Chowdhury, S. P., & Crossley, P., 2009. *Microgrids and active distribution networks*. London, UK: The Institute of Engineering and Technology. https://doi.org/10.1049/pbrn006e

Diaz-Gonzalez, F., Sumper, A., & Gomis-Bellmunt, O., 2016. *Energy storage in power systems*. West Sussex, UK: Wiley.

DigSILENT., n.d. PowerFactory applications. Retrieved from https://www.digsilent.de/en/powerfactory.html, accessed on 14/03/2019.

Ezennaya, O. S., Isaac, O. E., & Ezeanyim, O. I. C., 2014. Analysis of Nigeria's national electricity demand forecast (2013-2030). International Journal of Scientific & Technology Research, 3(3), 333-340.

Fichtner., 2018. Transmission expansion plan: development of power system master plan for the Transmission Company of Nigeria.

Foster, R., Ghassemi, M., & Cota, A., 2010. *Solar energy: renewable energy and the environment*. Boca Raton, FL: CRC Press.

Gao, D. W., 2015. *Energy storage for sustainable microgrid*. Oxford, UK: Academic Press. https://doi.org/10.1016/C2014-0-04144-5

Glover, J. D., Sarma, M. S., & Overbye, T. J., 2012. *Power system analysis and design*. (5th ed.). Stamford, CT: Cengage Learning.

GSA., n.d. Solar irradiance data obtained from World Bank via ENERGYDATA.info, under a project funded by the Energy Sector Management Assistance Program (ESMAP). For more information: http://globalsolaratlas.info

GWA., n.d. Wind data obtained from the Global Wind Atlas 2.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU) in partnership with the World Bank Group, utilizing data provided by Vortex, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info

Hatziargyriou, N. (Eds.)., 2014. *Microgrids: architectures and control*. West Sussex, UK: Wiley.

Ibrahim, S. S., Mukhtar, S., & Gani, I. B., 2017. Relationship between electricity consumption, manufacturing output and financial development : a new evidence from Nigeria. AESS Publications, 4(3), 28-35. https://doi.org/10.18488/journal.82.2017.43.28.35

Idris, N. A., Lamin, H. S., Ladan, M. J., & Yusuf, B. H., 2012. Nigeria's wind energy potentials : the path to a diversified electricity generation-mix. International Journal of Modern Engineering Research (IJMER), 2(4), 2434 - 2437.

IEA., 2018. Renewables information: overview.

Manwell, J. F., McGowan, J. G., & Rogers, A. L., 2009. *Wind energy explained: theory, design, and application*. (2nd ed.). West Sussex, UK: Wiley.

NERC., 2018. The grid code for the Nigerian electricity transmission system.

NERC., n.d. History, generation, transmission, and distribution. Retrieved from https://www.nercng.org/index.php/home/nesi/401-history, accessed on 16/03/2019.

NIPP., 2007. Integration and evacuation study for national integrated power projects.

Nwaneto, U. C., Akuru, U. B., Udenze, P. I., Awah, C. C., & Okoro, O. I., n.d. Economic implications of renewable energy transition in Nigeria.

Nwokoye, S. E., & Dimnwobi, S. K., 2017. Power infrastructure and electricity in Nigeria : Policy considerations for economic welfare. KIU Journal of Humanities, 2(1), 5-7.

Nwulu, N. I., & Agboola, O. P., 2011. Utilizing renewable energy resources to solve Nigeria's electricity generation. International Journal of Thermal & Environmental Engineering, 3(1), 15 - 20. https://doi.org/10.5383/ijtee.03.01.003

Ogunnubi, O., Ajala, O., & Idehen, I., 2017. A proposal for a microgrid service in urban. IEEE PES-IAS Power Africa, 474–478.

Okoronkwo, J. O., Ojo, O., & Davidson, I., 2016. Design considerations of the katsina wind farm in Nigeria. IEEE PES Power Africa Conference, 251–253.

Okundamiya, M. S., & Omorogiuwa, O., 2016. Analysis of an isolated micro-grid for Nigerian terrain. IEEE 59th International Midwest Symposium on Circuits and Systems (MWSCAS) Abu Dhabi, UAE.

Nelson, V., 2009. *Wind energy: renewable energy and the environment*. Boca Raton, FL: CRC Press.

PwC., 2016. Powering Nigeria for the future.

RECP., n.d. Nigeria: energy sector. Retrieved from https://www.africa-eu-renewables.org/market-information/nigeria/energy-sector, accessed on 03/03/2019.

Sambo, S. A., 2009. The place of renewable energy in the Nigerian energy sector.

TCN., n.d. Daily operational report. Retrieved from www.pwh.gov.ng, accessed on 29/01/2019.

Ter-Gazarian, A. G., 2011. *Energy storage for power systems*. (2nd ed.). London, UK: The Institute of Engineering and Technology.

Wind Europe., 2019. Wind energy in Europe in 2018: trends and statistics.

World Bank., 2018. Nigeria electrification project.

World Bank., n.d. Electric power consumption (kWh per capita). Retrieved from https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC, accessed on 03/03/2019.

Appendix 1

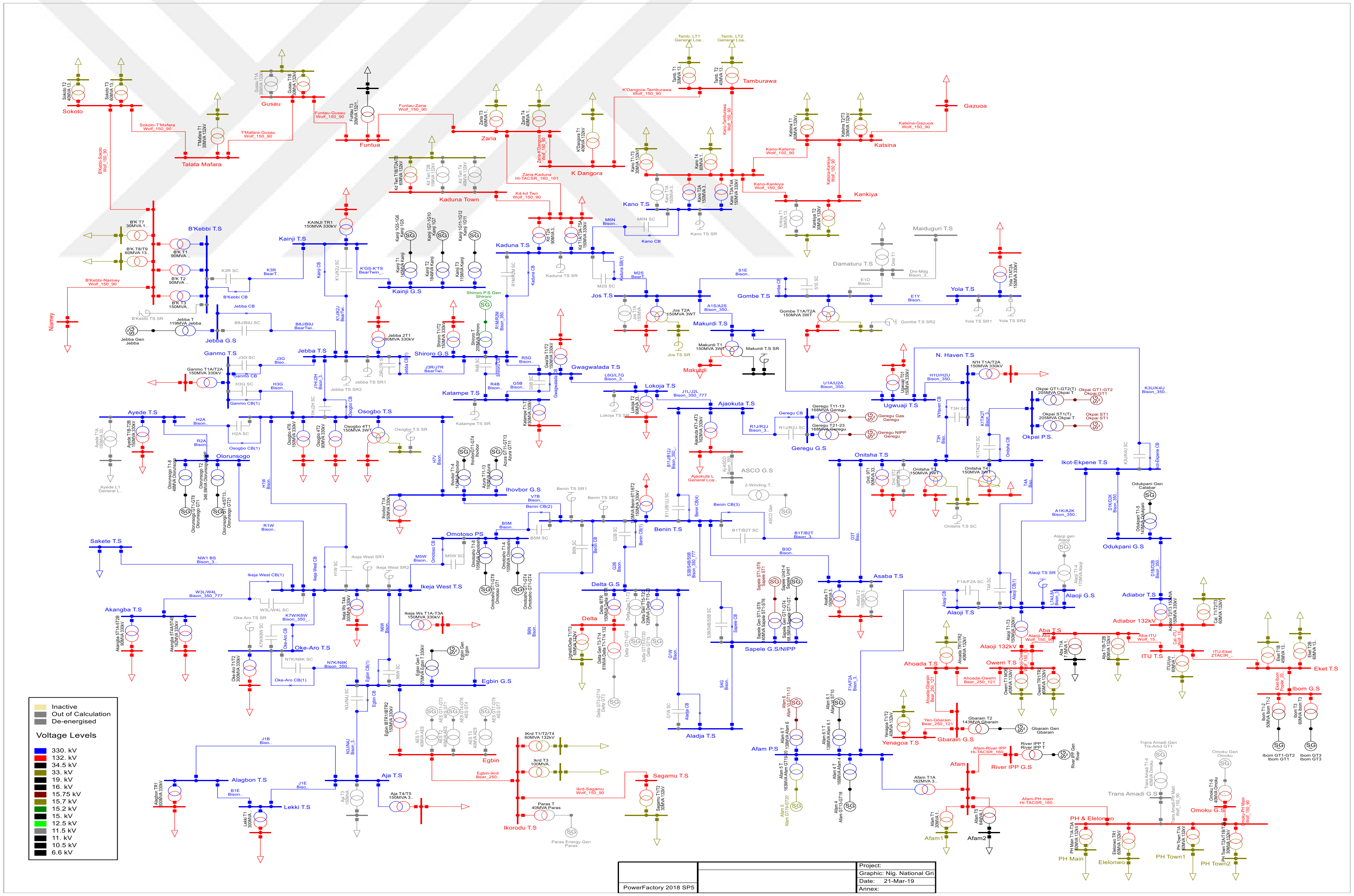


Fig. 22. Grid diagram showing the different voltage levels

Appendix 2

Table 12. Transmission Conductor Types (source: Fitchner, 2017)

Conductor Type	Circuit Type (SC or DC)	No. of Conductor/ Phase	Conductor Cross Sectional Area (mm2)	Thermal Rating (MVA)	+ve Sequence Impedance			Zero Sequence Impedance			Voltage Level
					Resistance (Ω/km)	Reactance (Ω/km)	Susceptance (μS/km)	Resistance (Ω/km)	Reactance (Ω/km)	Susceptance (μS/km)	
Bison, Twin	SC	2	350	777	0.0390	0.3310	3.4900	0.2760	0.9850	2.4900	330 kV OHL
	DC	2	350	1554	0.0394	0.3030	3.8120	0.2614	1.0019	2.2773	
Wolf, Single	SC	1	150	90	0.2220	0.4181	2.7368	0.4639	1.2986	1.7435	132 kV OHL
	DC	1	150	180	0.2223	0.4058	2.8285	0.4591	1.3263	1.7866	
Wolf, Twin	DC	2	150	180	0.1113	0.2809	4.0947	0.3481	1.2013	2.2723	
Hyena, Single	SC	1	100	65.5	0.2712	0.4640	0.0701	0.5620	1.6020	0.0480	
HI-TACSR, Single	SC	1	160	161	0.2272	0.2002	5.4886				
	DC	1	160	322	0.2681	0.2002	5.4886				
Bear, Single	SC	1	250	121	0.1328	0.3895	2.9432	0.2504	1.0133	1.6979	
	DC	1	250	242	0.1328	0.4000	2.8750	0.3806	1.2824	1.9266	
Bear, Double	DC	2	250	242	0.0666	0.2728	4.2237	0.3034	1.1932	2.3160	
Bear, Twin (Lion)	SC	2	250	240	0.0390	0.3310	3.4900	0.2760	0.9850	2.4900	330 kV OHL
	DC	2	250	480	0.0394	0.3030	3.8120	0.2614	1.0019	2.2773	
Cu/XLPE, Single	DC	1	400	141	0.0470	0.1413	50.2720	0.1410	0.4239	16.7469	132 kV OHL
ZTACIR, Single	SC	1	189.1	188	0.2898	0.3168	3.4688				
Panther, Single	DC	1	250	380	0.1363	0.3920	4.0312	0.3150	1.3490	1.3511	
Poplar, Single	DC	1	200	136.7	0.1800	0.2060	5.3348				
Dog, Single	SC	1	150								
Areo Z, Single	SC	1		90							

Appendix 3

Table 13. Transmission Conductor Data (source: Fitchner, 2017)

Node		Nomenclature	Length (km)	Circuit Type (Sc or Dc)	Conductor Type	Region
From	To					
Shiroro	Kaduna I	R1M	96	SC	Bison Twin	Kaduna
Shiroro	Kaduna II	R2M	96	SC	Bison Twin	
Kaduna	Kano	M6N	250	SC	Bison Twin	
Kaduna	Jos	M2S	197	SC	Bear Twin	
Kano	Zaria	Kano-Zaria	145	SC	Wolf, Single	
Kano	Hadeija	Kano-Hadeija	188	SC	Hyena, Single	
Kano	Kankia	Kano-Kankia	113.2	SC	Wolf, Single	
Kankia	Katsina	Kankia-Katsina	60	SC	Wolf, Single	
Katsina	Gazadua	Katsina-Gazaoa	43.75	SC	Wolf, Single	
Kano	Dan Agundi	Kunmbotso-Dan Agundi	8.75	SC	Wolf, Single	
Kumbotso	Dakata	Kunmbotso-Dakata	18	DC	Wolf, Single	
Kaduna	Kaduna town	Kaduna-Kaduna Town	14	SC	Wolf, Single	
Kaduna	Zaria	Kaduna-Zaria	72	SC	HI-TACSR, Single	
Zaria	Funtua	Zaria-Funtua	70	SC	Wolf, Single	
Funtua	Gusau	Funtua-Gusau	120	SC	Wolf, Single	
Gusau	Talata Mafara	Gusau-Talata Mafara	93	SC	Wolf, Single	
Tegina	Birnin Gwari	Tegina-Birnin Gwari	70	SC	Wolf, Single	
Osogbo	Ayede	H2A	119	SC	Bison Twin	Osogbo
Jebba	Osogbo	J1H	157	SC	Bison Twin	
Jebba	Osogbo	J2H	157	SC	Bison Twin	
Jebba	Ganmo	J3G	70	SC	Bison Twin	
Ganmo	Osogbo	H3G	87	SC	Bison Twin	
Osogbo	Ihobvor	H7V	226	SC	Bison Twin	
Ganmo	Ilorin	Ganmo-Ilorin	10.5	SC	Hyena, single	
Ganmo	Offa	Ganmo-Offa	44.73	DC		
Offa	Osogbo	Offa-Osogbo	47.6	SC	Hyena, single	
Osogbo	Iwo road	Osogbo-Iwo road	80	SC	Hyena, single	
Iwo road	Isheyin	Iwo-Isheyin	91	SC	Wolf, Single	
Iwo road	Ibadan North	Iwo-Ibadan North	36	SC	Wolf, Single	
Ibadan North	Aiyede	Ibadan-Ayede	14	SC	Wolf, Single	
Aiyede	Jericho road	Ayede-Jerico	6	SC	Wolf, Single	
Osogbo	Ilesha	Osogbo-Ilesha	17	SC	Wolf, Single	
Ilesha	Ife	Ilesha-Ife	19	SC	Wolf, Single	
Ife	Ondo	Ife-Ondo	58	SC	Wolf, Single	
Osogbo	Akure	Osogbo-Akure	200	SC	Hyena, single	

Node		Nomenclature	Length (km)	Circuit Type (Sc or Dc)	Conductor Type	Region
From	To					
Akure	Ado Ekiti	Akure-Ado Ekiti	35	DC	Panther, Single	
Benin	Egbin	B6N	218	SC	Bison Twin	Lagos
Egbin	Ikeja West	N6W	62	SC	Bison Twin	
Benin	Omotosho	B5M	120	SC	Bison Twin	
Omotosho	Ikeja West	M5W &	160	SC	Bison Twin	
Egbin	Oke Aro	N7K & N8K	55.8	DC	Bison Twin	
Oke Aro	Ikeja West	K7W K8W	27.9	DC	Bison Twin	
Egbin	Aja	N3J&N4J	15	DC	Bison Twin	
Ikeja West	Akangba	W3L&W4L	17.34	SC	Bison Twin	
Osogbo	Ikeja West	H1W	256.67	SC	Bison Twin	
Ikeja West	Olorunsogo	R1W	77	SC	Bison Twin	
Olorunsogo	Ayede	R2A	60	SC	Bison Twin	
Ayede	Osogbo	H2A	119	SC	Bison Twin	
Aja	Alagbon	Aja-Alagbon	26	DC	Bear, Double	
Ikeja West	Oworonshoki	Ikeja West-Oworonshoki	49	DC	Bear, single	
Oworonshoki	Akoka	Oworonshoki-Akoka	4	DC	Bear, single	
Akoka	Alagbon	Akoka-Alagbon	12.7	DC	Bear, single	
Amuwo	Ojo	Amuwo-Ojo	12.5	DC	Bear, single	
Akangba	Apapa Road	Akangba-Apapa Road	8.3	DC	Wolf, Twin	
Ijora	Akangba	Ijora-Akangba	8.3	DC	Wolf, Twin	
Ayede	Shagamu	Ayede-Shagamu	53.91	SC	Wolf, Single	
Shagamu	Ijebu Ode	Shagamu-Ijebu Ode	40.32	SC	Bear, Single	
Ogba	Papalanto	Ogba-Papalanto	44.28	SC	Wolf, Single	
Ikeja West	Agbara	Ikeja West-Agbara	32.04	DC	Bear, Single	
Ikeja West	Alimosho	Ikeja West-Alimosho	18.36	DC	Bear, Single	
Ikeja West	Ejigbo	Ikeja West-Ejigbo	13.32	DC	Bear, Single	
Ikeja West	Otta	Ikeja West-Otta	11.88	DC	Bear, Single	
Otta	Papalanto	Otta-Papalanto	11.88	DC	Bear, Single	
Egbin GS	Ikorodu	Egbin GS-Ikorodu	19.96	DC	Bear, Single	
Ikorodu	Egbin	Ikorodu-Egbin	19.5	DC	Bear, Single	
Ikorodu	Shagamu	Ikorodu-Shagamu	35.16	SC	Wolf, Single	
Agbara	Ojo	Agbara-Ojo	16.37	SC	Bear, Single	
Akangba	Itire	Akangba-Itire	3	DC	Bear, Single	
Itire	Ejigbo	Itire-Ejigbo	8	DC	Bear, Single	
Ejigbo	Ikeja West	Ejigbo-Ikeja West	13	DC	Bear, Single	
Akangba	Isolo	Akangba-Isolo	9	DC	Wolf, Single	
Ikeja West	Ilupeju	Ikeja West-Ilupeju	17	DC	Bear, single	
Ilupeju	Maryland	Ilupeju-Maryland	3	DC	Wolf, single	
Maryland	Ikorodu	Maryland-Ikorodu	20	DC	Bear, single	

Node		Nomenclature	Length (km)	Circuit Type (Sc or Dc)	Conductor Type	Region
From	To					
Papalanto	Abeokuta	Papalanto-Abeokuta	35	SC	Bear, Single	
Alimosho	Ogba	Alimosho-Ogba	19	DC	Bear, Single	
Ayede	Jericho	Ayede-Jericho	2	SC	Wolf, Single	
Ogba	Alausa	Ogba-Alausa	7.5	DC	Bear, Single	
Osogbo	Ilorin	Osogbo-Ilorin	78.46	SC	Wolf, Single	
Osogbo	Omuaran	Osogbo-Omuaran	47.53	SC	Wolf, Single	
Osogbo	Ayede	Osogbo-Ayede	37.15	SC	Bear, Single	
Osogbo	Ife	Osogbo-Ife	33.13	SC	Wolf, Single	
Ife	Ondo	Ife-Ondo	58.05	SC	Wolf, Single	
Osogbo	Ilesa	Osogbo-Ilesa	16.4	SC	Wolf, Single	
Osogbo	Akure	Osogbo-Akure	95	SC	Wolf, Single	
Shiroro	Kaduna	R1M	96	SC	Bison Twin	Shiroro
Shiroro	Kaduna	R2M	96	SC	Bison Twin	
Jebba	Shiroro	J3R	230.43	SC	Bear Twin (Lion)	
Jebba	Shiroro	J7R	230.43	SC	Bear Twin (Lion)	
Kainji GS	Jebba	K1J & K2J	81	SC	Bear Twin (Lion)	
Kainji GS	Jebba	Kainji – Jebba II	81	SC	Bear Twin (Lion)	
Jebba GS	Jebba TS	B8J	8	DC	Bear Twin (Lion)	
Jebba GS	Jebba TS	B9J	8	DC	Bear Twin (Lion)	
Jebba	Osogbo	J1H	157	SC	Bison Twin	
Jebba	Osogbo	J2H	157	SC	Bison Twin	
Jebba	Ganmo	J3G	70	SC	Bison Twin	
Oshogbo	Ganmo	H3G	83.81	SC	Bison Twin	
Kainji	Birnin Kebbi	K3R	310	SC	Bear Twin (Lion)	
Shiroro	Katampe TS	R4B	144	SC	Bison Twin	
Shiroro	Gwagwalada	R5G	144	SC	Bison Twin	
Gwagwalada	Katampe	G5B	60	SC	Bison Twin	
Gwagwalada	Eastmain		42	DC	Bison Twin	
Shiroro	Minna	Shiroro-Minna	68	DC	Wolf, Single	
Minna	Suleja	Minna-Suleja	99	DC	Wolf, Single	
Suleja	Katampe	SulejaAbuja	55	DC	Wolf, Single	
Karu	Keffi	Abuja-Keffi	67	SC	Wolf, Single	
Tegina	Birnin gwarri	Tegina-Birnin Gwari	80	SC	Wolf, Single	
Keffi	Akwanga	Keffi-Akwanga	62.5	SC	Wolf, Single	
Akwanga	Lafia	Akwanga-Lafia	60	DC	Bear, Single	
Shiroro	Tegina	ShiroroTegina	90	SC	Wolf, Single	
Birnin Kebbi	Niamey	Birnin Kebbi-Niamey	250	SC	Wolf, Single	
Birnin Kebbi	Sokoto	Birnin Kebbi-Sokoto	130	SC	Wolf, Single	
Sokoto	Talata Mafara	Sokoto-Talata Mafara	142	SC	Wolf, Single	
Minna	Bida	MinnaBida	78.38	SC	Wolf, Single	

Node		Nomenclature	Length (km)	Circuit Type (Sc or Dc)	Conductor Type	Region
From	To					
Tegina	Kontagora	Tegina	84.44	SC	Wolf, Single	
Eastmain	Kukwaba	East-Kukwaba	24	DC	Bear, Single	
Katampe	Kukwaba	Katampe-Kukwaba	8.9	DC	Cu/XLPE, Single	
Kukwaba	Apo	Kukwaba-Apo	24	DC	Bear, Single	
Apo	Katampe	Apo-Katampe	25	DC	Bear, Single	
Katampe	Central Area	Katampe-Central Area	15	DC	Bear, Single	
Karu	Apo	Karu-Apo	10	SC	Bear, Single	
Eastmain	Kukwaba	Eastmain-Kukwaba	24	DC	Bear, Single	
Benin	Onitsha	B1T & B2T	137	DC	Bison Twin	Benin
Benin	Omotosho Phase I	B5M	120	SC	Bison Twin	
Omotosho Phase I	Ikeja West	M5W	160	SC	Bison Twin	
Benin	Egbin G.S.	B6N	218	SC	Bison Twin	
Osogbo	Ihovbor NIPP	H7V	251	SC	Bison Twin	
Ihovbor NIPP	Benin	V7B	17.7	SC	Bison Twin	
Benin	Ajaokuta	B11J & B12J	205.15	DC	Bison Twin	
Sapele	Aladja	S4G	61.25	SC	Bison Twin	
Delta GS	Benin	G3B	52.65	SC	Bison Twin	
Delta GS	Aladja	G1W	29.5	DC	Bison Twin	
Sapele	Benin	S3B & S4B	52.65	DC	Bison Twin	
Sapele	Benin	S5B	52.65	DC	Bison Twin	
Lokoja	Gwagwalada	L6G	160	SC	Bison Twin	
Ajaokuta	Geregu	R1J	80	SC	Bison Twin	
Ajaokuta	Geregu	R2J	80	SC	Bison Twin	
Ajaokuta	Lokoja	J1L&J2L	38	DC	Bison Twin	
Delta GS	Benin	Delta-Benin	102.41	SC	Bear, Single	
Delta GS	Benin	Delta-Benin	102.41	DC	Bear, Single	
Benin	Irrua	Benin-Irrua	81	SC	Wolf, Single	
Irrua	Ukpilla	Irrua-Ukpilla	43	SC	Wolf, Single	
Ukpilla	Okene	Ukpilla-Okene	33	SC	Wolf, Single	
Okene	Ajaokuta	Okene-Ajaokuta	60	SC	Wolf, Single	
Okene	Itakpe	Tee-off/Itakpe	41.7	SC	Wolf, Single	
Delta II	Effurun	Delta-Efurun	32.04	SC	Wolf, single	
Ajaokuta	Itakpe	AjaokutaItakpe	45	SC	Wolf, Single	
Ajaokuta	Ajaokuta Steel Works	Ajaokuta-Steel Works	3.9	SC	Wolf, Single	
Ajaokuta	Ajaokuta Town	Ajaokuta-Ajaokuta Town	10	SC	Wolf, Single	
Afam	Alaoji	F1A & F2A	28.8	DC	Bison Twin	Port Harcourt
Onitsha	Alaoji	T4A	138	SC	Bison Twin	
Calabar PS	Calabar SS	Calabar PS-Calabar SS	17.7	DC	Bison Twin	

Node		Nomenclature	Length (km)	Circuit Type (Sc or Dc)	Conductor Type	Region
From	To					
Alaoji	Aba	Alaoji-Aba	7.7	DC	Wolf, Single	
Afam GS	Alaoji	Afam-Alaoji	28.7	DC	HI-TACSR, Single	
Afam GS	Port-Harcourt Main	Afam-Port Harcourt Main	37.8	DC	HI-TACSR, Single	
Port-Harcourt Main	Port-Harcourt Town	PH Mains-PH Town	3	DC	Wolf, Single	
Trans Amadi	Ahoada	Trans Amadi-Ahoada		DC		
Aba	Itu	Aba-Itu	85.4	SC	Wolf, Single	
Uyo	Eket	Itu-Eket	74.55	SC	ZTACIR, Single	
Uyo	Itu	Uyo-Itu	18	SC	ZTACIR, Single	
Itu	Calabar	Itu-Calabar	47.36	SC	Wolf, Single	
Alaoji	Owerri	Alaoji-Owerri	60	DC	Wolf, Single	
Owerri	Ahoada	Owerri-Ahoada	73	DC	Bear, Single	
Aba	Alaoji	Aba-Alaoji	15	DC	Bear, Single	
Alaoji	Umuahia	Alaoji-Umuahia	50	DC	Bear, Single	
Alaoji	Owerri	Alaoji-Owerri	10	DC	Panther, Single	
Ahoada	Yenagoa	Ahoada-Yenagoa	40	DC	Panther, Single	
IBOM G.S.	Eket	Ibom-Eket	45	DC	Poplar, single	
Onitsha	New Haven	T3H	96	SC	Bison Twin	Enugu
Okpai	Onitsha	K1T & K2T	56	DC	Bison, Twin	
Ugwuaji	New Haven	Ugwuaji-New Haven	7	DC	Bison, Twin	
Onitsha	Oji River	Onitsha-Oji River	63.85	SC	Wolf, Single	
Onitsha	Awka	Onitsha-Awka	30	SC	Wolf, Single	
Awka	Oji River	Awka-Oji River	33	SC	Wolf, Single	
Onitsha	GCM	Onitsha-GCM	8.05	SC	Wolf, Single	
New Haven	Oji River	New Haven-Oji River	44.1	SC	Wolf, Single	
New Haven	Oturkpo	New HavenOturkpo	160.3	SC	Wolf, Single	
Oturkpo	Aliade	Oturkpo-Aliade	39	SC	Wolf, Single	
Aliade	Markudi	Aliade-Makurdi	50	SC	Bear, single	
Aliade	Yandev	Aliade-Yandev	60	SC	Wolf, Single	
New Haven	Nkalagu	New HavenNkalagu	38.85	DC	Wolf, Single	
Nkalagu	Abakaliki	NkalaguAbakaliki	54.25	SC	Wolf, Single	
Jos	Gombe	SIE	265	SC	Bison, twin	Bauchi
Kaduna	Jos	M2S	197	SC	Bison, twin	
Gombe	Damaturu	E1D	160	SC	Bison, twin	
Damaturu	Maiduguri		260	SC	Bison, twin	
Gombe	Yola	E1Y	240	SC	Bison, twin	
Yola	Jalingo		140	SC	Bison, twin	
Jos	Bauchi, Gombe	Jos-Bauchi-Gombe	320	SC	Wolf, Single	
Jos	Bauchi	Jos-Bauchi	118	SC	Wolf, Single	

Node		Nomenclature	Length (km)	Circuit Type (Sc or Dc)	Conductor Type	Region
From	To					
Bauchi	Gombe	Bauchi-Gombe	146	SC	Wolf, Single	
Gombe	Dadin Kowa	Gombe-Dadin Kowa	49	SC	Wolf, Single	
Dadin Kowa	Biu	Dadin Kowa-Biu		SC		
Biu	Damboa	Biu-Damboa	142	SC	Hyena, Single	
Damboa	Maiduguri	Damboa-Maiduguri	71	SC	Hyena, Single	
Gombe	Ashaka	Gombe-Ashaka	84	SC	Wolf, Single	
Ashaka	Potiskum	Ashaka-Potiskum	94	SC	Wolf, Single	
Gombe	Ashaka	Ashaka-(Tee-off)	11	SC	Wolf, Single	
Gombe	Savanah, Yola	Gombe-SavanahYola	258.65	SC	Wolf, Single	
Gombe	Savannah	Gombe-Savanah	92	SC	Hyena, Single	
Savannah	Numan	Savannah-Numan	85	SC	Hyena, Single	
Numan	Yola	Numan-Yola	50	SC	Wolf, Single	
Gombe	Savanah	Savanah-(Tee-off)	3	SC	Dog, Single	
Jos	Mekeri	Jos-Makeri	28.5	DC	Wolf, Single	
Makeri	Pankshin	Makeri-Pankshin	109.5	SC	Wolf, Single	
Ikeja West	Sakete		50	SC	Bison, Twin	Inter-national
Birnin-Kebbi	Niamey	Birnin Kebbi-Niamey	264	SC	Areo Z, Single	
Katsina	Gazuoa	Katsina-Gazuoa	72	SC	Wolf, Single	

Appendix 4

Table 14. Transmission Substation Transformers (data obtained from TCN)

	STATION	TX NOM.	TX RATING (MVA)	AVAILABLE CAPACITY (MVA)	RATING (kV)	MAKE	DISCO
	SHIRORO REGION						
1	SHIRORO	T1	150	150	330/132/11	EMCO	ABUJA
		T2	150	150	330/132/11	MITSUBISHI	
2	SHIRORO II	T1	30	30	132/33	OEL	
3	MINNA	T1	60	60	132/33	LEEEC	
		T2	30	30	132/33	TRAFO-UNION	
		TR7	60	60	132/33	TRANF/RECTIFIER	
4	TEGINA	T1	30	30	132/33	TELK	ABUJA/KADUNA
5	JEBBA T.S.	2T1	80	80	330/132/13.8	MARILLI	ABUJA/IBADAN
		2T2	30	30	132/33	ABB P. TECH	
6	BIDA	T1	30	30	132/33	TRAFO-UNION	ABUJA
		T2	30	30	132/33	MITSUBISHI	
7	KAINJI T.S.	TR1	150	150	330/132/33	MBH POWER	
		T1	40	40	132/33	MBH POWER	
		T2	40	40	132/33	MBH POWER	
8	KONTAGORA	T1	30	30	132/33	TOSHIBA	
		T2	60	60	132/33	LEEEC	
9	BIRNI-KEBBI	T1	90	90	330/132/33	SAVIGLINO	KADUNA
		T2	90	90	330/132/33	ASGEN	
		(T3) MBH	150	150	330/132/34	MBH POWER	
		T7	30	30	132/33	HAWKER SYDNEY	
		T8	60	60	132/33	PAULWELS	
		(T9) MBH	60	60	132/33	MBH POWER	
10	SOKOTO	T1	30/40	40	132/33	TOSHIBA	
		T2	30/40	40	132/33	TOSHIBA	
		NEW T3	60	60	132/33	LEEC	
	KADUNA REGION						
1	KADUNA T. S.	T1A	150	150	330/132	MARELLI	KADUNA
		T2A	90	90	330/132	ASGEN	
		T3A	150	150	330/132	MARELLI	
		T4A	150	150	330/132	ASGEN	
		T5A	150	150	330/132	MISUBISHI	
		T1	60	60	132/33	CROMPTON GREEVES	
		T2	60	60	132/33	AREVA	

	STATION	TX NOM.	TX RATING (MVA)	AVAILABLE CAPACITY (MVA)	RATING (kV)	MAKE	DISCO
		T3	60	60	132/33	ABB	
		T4	60	60	132/33	PAUWELS	
2	KADUNA TOWN	T1A	60	60	132/33	TOSHIBA	
		T1B	60	60	132/33	CROMPTON GREEVES	
		T2A	60	60	132/33	LEEC	
		T2B	15	15	132/11	ABB	
		T3	60	60	132/33	LEEC	
		T4(MOB)	40	40	132/33	TRANSFORMERS AND RECT	
3	ZARIA	T3	60	60	132/33KV		
		T4	40	40	132/33KV	FERRANTI	
4	FUNTUA	T1	7.5	7.5	132/33	TRANSFORMERS AND RECT	KANO
		T2	7.5	7.5	132/11	PAUWELS	
		T3	30	30	132/11	BRUSH	
		T4	40	40	132/33	ASEA	
5	GUSAU	T1A	30	30	132/33		KADUNA
		T1B	30	30	132/33	PAUWELS	
6	T-MAFARA	T1	30	30	132/33	CENEMES	
7	KANO	T1A	150	150	330/132/33	ABB TECH	KANO
		T2A	150	150	330/132/33		
		T3A	150	150	330/132/33	C.GREAVES	
		T4A	150	150	330/132/33	MISUBISHI	
		T1	30	30	132/33	C.GREAVES	
		T2	30/40	30	132/33	MBH POWER	
		T3	30	30	132/33	TOSHIBA	
		T4	60	60	4	ABB	
8	DAN-AGUNDI	T1	60	60	132/33	ABB TECH	
		T2	60	60	132/33KV	TRANS/RECTIFIERS	
		T3	60	60	132/33	PAUWELS	
9	DAKATA	T1	60	60	132/33	PAUWELS	
		T2	60	60	132/33	ABBPOWERTECK	
		T3	30	30	132/33	PAUWEL-TRAFO	
10	KANKIA	T1	30	30	132/33	PAUWEL-TRAFO	
		T2	30	30	132/33	PAUWELS TRAFO	
11	KATSINA	T1	60	60	132/33	PAUWELS	

	STATION	TX NOM.	TX RATING (MVA)	AVAILABLE CAPACITY (MVA)	RATING (kV)	MAKE	DISCO
		T2	30	30	132/33	PAUWEL	
		T3	30	30	132/33	ELKA	
12	HADEJIA	T1	7.5	7.5	132/33	PAUWELS	
		T2	15	15	132/33	PAUWELS	
		T3	60	60	132/33KV	PAUWELS	
13	DUTSE	T1	30/40	40	132/33	FERRANTI	
		T2	30/40	40	132/33	LEEEC	
14	AZARE	T1	30/40	30	132/33	ABB	JOS
		T2	30/40	30	132/33	ABB	
15	K/DANGORA	T1	30/40	40	132/33	ABB	KANO
16	DAURA	TI	30/40	40	132/33		
		T2	30/40	30	132/33		
17	TAMBURAWA	T1	30/40	30	132/33	CHINT	
		T2	30/40	40	132/33	TRAFO-UNION	
BAUCHI REGION							
1	JOS	T1A	150	150	330/132/33	MITSUBISHI	JOS
		T2A	150	150	330/132/33	ARAVA	
		T1	60	60	132/33	ELRA	
		T2	60	60	132/33	ELRA	
		T5	60	60	132/33	TOSHIBA	
2	BAUCHI	T3	40	40	132/33	TELK	
		T4	30/40	40	132/33	ABB	
		T5	60	60	132/33	LEEC	
3	MAKERI	T1	60	60	132/33	CHANGCHUN SANDING	
		T2	60	60	132/33	CHANGCHUN SANDING	
4	GOMBE	T1A	150	150	330/132/33	MITSUBISHI	
		T2A	150	150	330/132/33	ABB	
		T1	30/45	30	132/33/11	HYUNDAI	
		T2	60	60	132/33	LEEEC	
		T3	30	30	132/33	LEEECHUN	
5	ASHAKA	T1	30	30	132/11	HAWKER SIDDELEY	
		T2	20	20	132/11	FERRANTI	
6	KAFANCHAN	MOB	40	40	132/33	IRAN TRANSFO	KADUNA
7	POTISKUM	T1	30	30	132/33	GEM	YOLA
		T2	30	30	132/33	TOSHIBA	

	STATION	TX NOM.	TX RATING (MVA)	AVAILABLE CAPACITY (MVA)	RATING (kV)	MAKE	DISCO
8	BIU	T1	15	15	132/33	FERRANTI	
		T2	30/40	30	132/33	TOSHIBA	
9	MAIDUGURI	T1	45	45	132/33	HYUNDAI	
		T2	45	45	132/33	HYUNDAI	
		T3	15	15	132/33	FERRANTI	
10	DAMBOA	T1	30	30	132/33	TOSHIBA	
11	YOLA	T1A	150	150	330/132/33	SIEMENS	
		T2A	150	150	330/132/33	SIEMENS	
		T1-A	30	30	132/33	LEECHUM	
		T1-B	60	60	132/33	LEECHUM	
12	SAVANNAH	T1	15	15	132/33	G .E. M .	
13	JALINGO	T1A	30/40	40	132/33	STEN	
		T1B	30/40	40	132/34	STEN	
14	MAYO BELWA	T1	30/40	40	132/33	STEN	
LAGOS REGION							
1	AKANGBA	5T1A	109/90/30	90	330/132/13.8	ASGEN	EKO/IKEJA
		5T1B	109/90/30	90	330/132/13.8	MITSUBISHI	
		5T2A	109/90/30	90	330/132/13.8	MITSUBISHI	
		5T2B	109/90/30	90	330/132/13.8	ASGEN	
		5T4A	162/150/50	150	330/132/33	MITSUBISHI	
		5T4B	162/150/50	150	330/132/33	INDIA	
		10T1A	60	60	132/33	A.B.B.	
		10T1B	60	60	132/33	INDIA	
		10T2A	60	60	132/33	ABB	
		10T2B	60	60	132/33	INDIA	
		10T3A	60	60	132/33	MITSUBISHI	
2	ILUPEJU	T1	15	15	132/11	OEL	EKO
		T2	45/30/15	30	132/33/11	MINEL	
		T3	15	15	132/11	OEL	
		T4	30	30	132/33	PAUWEL	
3	IJORA	T1A	30	30	132/33	G.E.C.	
		T1B	30	30	132/33	G.E.C.	
		T2A	45/30/15	30	132/33/11	HYUNDAI	

	STATION	TX NOM.	TX RATING (MVA)	AVAILABLE CAPACITY (MVA)	RATING (kV)	MAKE	DISCO
		T2B	30	30	132/33	G.E.C.	
4	OJO	T1	30	30	132/33	C.E.N	
		T3	60	60	132/33	ABB P TEC.	
		T4	60	60	132/33	ABB P TEC.	
5	ISOLO	T1	60	60	132/33	INDIA	EKO/IKEJA
		T2	60	60	132/33	BBC	
		T3	45/30/15	30	132/33	BBC	
6	ITIRE	T1	30	30	132/33	MITSUBISHI	
		T2	60	60	132/33		
		T3	40	40	132/33	ABB POWER TECH	
7	EGBIN	IBTR1	150	150	330/132/33	MITSUBISHI	IKEJA
		IBTR2	150	150	330/132/33	MISUBISHI	
8	MARYLAND	T1	22.5/30	30	132/33	MITSUBISHI	
		T2	60	60	132/33	CHANGODAR	
		T3	30	30	132/33	MITSUBISHI	
9	IKORODU	T1	60	60	132/33	ABB POWER TECH	
		T2	60	60	132/33	ABB POWER TECH	
		T3	100	100	132/33	LEEEC	
		T4	60	60	132/33/11	TOSHIBA	
10	ODOGUNYAN	T1-60MVA	60	60	132/33/11	PAUWELS-TRAFO	
		T2-60MVA	60	60	132/33/11	PAUWELS-TRAFO	
		T4	60	60	132/33/11	TOSHIBA	
11	AJA	T3	150	150	330/132/33	MITSUBISHI	EKO
		T4	150	150	330/132/33	PAUWELS	
		T5	150	150	330/132/33	AREVA	
		TR1	60	60	132/33	MITSUBISHI	
		TR2	60	60	132/33	PAUWELS	
		TR8	60	60	132/33	ATLANTA	
		T7	100	100	132/33	SHANDONG	
12	ALAGBON	TR1	300	300	330/132/33	SPECO	
		T1	66	66	132/33	ELTA	
		T2	66	66	132/33	ELTA	
		TR11	60	60	132/33	AREVA	
		TR12	60	60	132/33	AREVA	
		MOB-60	60	60	132/33	ATLANTA	
13	APAPA-ROAD	T1	45/30/15	30	132/33	HYUNDAI	

	STATION	TX NOM.	TX RATING (MVA)	AVAILABLE CAPACITY (MVA)	RATING (kV)	MAKE	DISCO
		T2	45/30/15	30	132/33	ITAL TRAFO	
14	AKOKA	T1	45/30/15	30	132/33	TOSHIBA	EKO/IKEJA
		T3	40	40	132/33	TOSHIBA	
15	OWORONSHOKI	T1	60	60	132/33	CROMPTON GREAVES	IKEJA
		T2	60	60	132/33	CROMPTON GREAVES	
16	AMUWO-ODOFIN	T1	60	60	132/33	TOSHIBA	
		T2	30	30	132/33	MITSUBISHI	
		T3	30	30	132/33	TOSHIBA	
		T4	40	40	132/34	TOSHIBA	
17	LEKKI	T1	300	300	330/132/33	SPECO	EKO/IKEJA
		T2	300	300	330/132/33	SPECO	
		TR1	60	60	132/33	AREVA	
		TR2	60	60	132/34	AREVA	
18	IKEJA WEST	T1A	150	150	330/132/33	MITSUBISHI	IKEJA
		T1B	150	150	330/132/33	AREVA	
		T2A	150	150	330/132/33	MITSUBISHI	
		T2B	150	150	330/132/33	MITSUBISHI	
		T3A	150	150	330/132/33	AREVA	
		T4A	300	300	330/132/33	AREVA	
19	OGBA	T1	60/40/20	60	132/33	TOSHIBA	
		T2	60	60	132/33	PAUWELL	
		T3	60	60	132/33	PAUWELL	
		MOB-45/30/2O	30	30	132/34	MITSUBISHI	
			20	20	132/11	MITSUBISHI	
20	ALIMOSHO	T1	30	30	132/33	MITSUBISHI	
		T2	100	100	132/33	SPECO	
		T3	100	100	132/33	GDIANGSU HUAPENG	
21	EJIGBO	T1	100	100	132/33	GDIANGSU HUAPENG	
		T2	30	30	132/33	ITAL TRAFO	
		T3	60	60	132/33	STECO	

	STATION	TX NOM.	TX RATING (MVA)	AVAILABLE CAPACITY (MVA)	RATING (kV)	MAKE	DISCO
		MOB-40MVA	40	40	132/33		
22	AGBARA	T1	45/30/15	30	132/33	HYUNDAI	EKO
		T2	45/30/15	30	132/33	HYUNDAI	
		T3	60	60	132/33	CROMPTOM	
23	ALAUSA	T1	45/30/15	30	132/33	HYUNDAI	IKEJA
		T2	30	30	132/33	ELTA	
		T3	60	60	132/33	PAUWELS	
24	AYOBO	T1	60	60	132/33	PAUWELS	
		T2	60	60	132/33	PAUWELS	
25	OTTA	T1	40	40	132/33	MINEL EMCO	IBADAN
		T2	60	60	132/33	PAUWELS	
		T3	45/30	30	132/33	BBC	
		MOB	40/30/20	40	132/33	CG ELECT.SYSTEM	
26	PAPALANTO	T1	15	15	132/33	TRAFO-UNION	
		T2	30	30	132/33	TOSHIBA	
		T3	30	30	132/33	ABB	
27	ABEOKUTA	T1	30	30	132/33	ELTA	
		T2	60	60	132/33	JSHP	
		T3	30	30	132/33	PAUWEL	
28	OKE-ARO	T1	300	300	330/132/33	CROMPTOM GREAVES	
		T2	300	300	330/132/33	CROMPTOM GREAVES	
		T5	60	60	132/33	CROMPTOM GREAVES	
		T6	60	60	132/33	CROMPTOM GREAVES	
OSOGBO REGION							
1	OSOGBO	4T1	150	150	330/132/33	CROMPTON GREAVES	OSOGBO
		4T6	150	150	330/132/33	AREVA	
		4T2	90	90	330/132/13.8	MITSUBISHI	
		4T3	60	60	132/33	T & R	
		4T4	60	60	132/33	T&R	

	STATION	TX NOM.	TX RATING (MVA)	AVAILABLE CAPACITY (MVA)	RATING (kV)	MAKE	DISCO
		4T5	30	30	132/33	MITSUBISHI	
2	IFE	T1	30	30	132/33	ELTA	
		T2	30	30	132/33	ELTA	
3	ILESA	T1	40/30	40	132/33	ABB POWER TECH	
		T2	40/30	40	132/33	ABB POWER TECH	
4	OFFA	T1	30	30	132/33	TOSHIBA	
5	GANMO	T1A	150	150	330/132/33	CROMPTON GREAVES	
		T2A	150	150	330/132/33	CROMPTON GREAVES	
		T1	60	60	132/33	SIEMENS	
		T2	60	60	132/33	SIEMENS	
6	ILORIN	T1A	60	60	132/33	TOSHIBA	
		T2A	45/30	30	132/33	HYUNDAI	
7	OMU-ARAN	T1	30	30	132/33	MITSUBISHI	
		T2	30	30	132/33	TOSHIBA	
8	ADO EKITI	T1	40/30	40	132/33	ABB	BENIN
		T2	40/30	40	132/33	ABB	
		T3	66	66	132/33	JSHP	
9	AYEDE 330kV T.S.	T1A	150	150	330/132/33	LEEEC	IBADAN
		T1B	150	150	330/132/33	AREVA	
		T2A	150	150	330/132/33	MITSUBISHI	
		T2B	150	150	330/132/34.5	CROMPTON GREAVES	
	AYEDE 132kV T.S.	T1	100	100	132/33	GET	
		T2	60	60	132/34	EMCO	
		T3	60	60	132/33	PAUWEL TRA	
10	JERICHO	T1	45/30/15	30	132/33	MITSUBISHI	
		T2	40	40	132/33	PAUWELS	
11	IBADAN NORTH	T1	60	60	132/33	LEEEC	
		T2	60	60	132/33	TELK	
12	SAGAMU	T1	30	30	132/33	ELTA	
		T2	30	30	132/33	ELTA	
13	IJEBU-ODE	T1	30	30	132/33	ELTA	
		T2	30	30	132/33	ELTA	
		T3	60	60	4	EMCO	
14	ISEYIN T.S.	T1	45/30	30	132/33	HYUNDAI	

	STATION	TX NOM.	TX RATING (MVA)	AVAILABLE CAPACITY (MVA)	RATING (kV)	MAKE	DISCO
		T2	45/30	30	132/33	MITSUBISHI	
15	IWO T.S.	T1	28/40	40	132/33	LEEC	
16	McPHERSON	T1	28/40	40	132/33	LEEC	
BENIN REGION							
1	BENIN	6T1	150	150	330/132/33	MITSUBISHI	BENIN
		6T2	150	150	330/132/33	MITSUBISHI	
		T21	60	60	132/33	INDIAN T & R	
		T22	80	80	132/33	ABB-TECH	
		T23	60	60	132/33	PAUWELLS	
		T24	60	60	132/33	SPECO	
2	IRRUA	T1	60	60	132/33	ABB TECH.	
		T2	30	30	132/33	ABB TECH.	
3	OGHARA	T1	30	60	132/33	CHAN HUAB	
		T2	30	30	132/33	CHAN HUAB	
4	EFFURUN	T21	60	60	132/33	FERRANTI	
		T22	60	60	132/33	ELTA	
		T23	60	60	132/33	PAUWELLS	
5	AMUKPE	T1	30/40	40	132/33	STEM	
		T2	60	60	132/33	LEEC	
6	UGHELLI/DELTA	IBTR	150	150	330/132	MITSUBISHI	BENIN
		T1	60	60	132/33	HYUNDAI	
		T2	30	30	132/33	ELTA	
		T3	60	60	132/33	ELTA	
7	IHOVBOR	T1A	150	150	330/132	SIEMENS	
		T1	60	60	132/33	SPECO	
		T12	60	60	132/33	SPECO	
8	OKADA	T2	40	40	132/33	MHB POWER	BENIN
9	ONDO	T1	30	30	132/33	ELTA	
		T2	30	30	132/33	ELTA	
10	AKURE	T1A	30	30	132/33	ABB	
		T2A	30	30	132/33	MITSUBISHI	
11	OMOTOSHO	T1A	150	150	132/33	PAUWELLS	
		T3A	60	60	132/33	PAUWELLS	
ENUGU REGION							
1	NEW HAVEN	T1A	150	150	330/132/33	MITSUBISHI	ENUGU
		T2A	150	150	330/132/33	MITSUBISHI	
		TR1	30	30	132/33	LEE CHUM	
		TR2	30	30	132/33	LEE CHUM	

	STATION	TX NOM.	TX RATING (MVA)	AVAILABLE CAPACITY (MVA)	RATING (kV)	MAKE	DISCO
		TR3	60	60	132/33	LEE CHUM	
		TR4	60	60	132/33	EMCO	
2	UGWUAJI	T01	150	150	330/132/34.5	CROMPTON GREAVES	
		T03	60	60	132/34.6	CROMPTON GREAVES	
3	ABAKALIKI	T1	30	30	132/33	ABB	ENUGU/PH
		T2	60	60	132/33	INDIAN LTD	
4	OTURKPO	T1	7.5	7.5	132/33	PAUWELS	JOS
		MOB	40	40	132/33		
		T2	30	30	132/33	ABB	
5	NKALAGU	T1A	30	30	132/33	GEN. ELECT.	ENUGU
		T2A	30	30	132/33	ESPANOLA	
6	YANDEV	T1	15	15	132/33	FERRENTI	JOS/YOLA
		T2	60	60	132/33	LEEEC	
		MOB	45	45	132/33/11	MITSUBISHI	
7	MAKURDI	T1	150	150	330/132/34.5	AREVA	JOS
		T2	60	60	132/34.5	AREVA	
		MOB	40	40	132/33	ABB	
8	ONITSHA	9T1	90	90	330/132/13.8	MITSUBISHI	ENUGU
		9T2	90	90	330/132/13.8	ASGEN	
		T3	150	150	330/132/33	AVERA	
		T4	150	150	330/132/33	AVERA	
		MOB	45	45	132/33	MITSUBISHI	
		MOB	45	45	132/11	MITSUBISHI	
		TR11	60	60	132/33	HYUNDAI	
		TR12	15	15	132/11	TRAFO-UNION	
		TR13	60	60	132/33	PAUWEL	
		TR14(MOB2)	40	40	132/33	CG ELECT.SYSTEM	
9	ASABA	T1	150	150	330/132/33	SIEMENS(CROATIA)	BENIN
		T2	150	150	330/132/33		
		TR1	60	60	132/33	AREVA	
		TR2	60	60	132/33	AREVA	
10	GCM	TR1	60	60	132/33		
11	AGBOR	TR1	60	60	132/33		
		TR2	60	60	132/33		
12	AWKA	TR1	30	30	132/33	ABB	ENUGU

	STATION	TX NOM.	TX RATING (MVA)	AVAILABLE CAPACITY (MVA)	RATING (kV)	MAKE	DISCO
		TR3	30	30	132/33	PAUWEL TRAFO	
13	AGU-AWKA	MOB	40	40	132/33	LEEEC	
14	NSUKKA	T1A	7.5	7.5	66/33	TRAFO-UNION	
		T1B	7.5	7.5	66/33	FOSTER	
15	OJI TS	T1A	30	30	132/33	PAUWELL	
		T1B	15	15	132/66	SAVIGLIANO	
PORT HARCOURT REGION							
1	ALAOJI	T1A	150	150	330/132/33	MITSUBISHI	ENUGU/PH
		T2A	150	150	330/132/33	MITSUBISHI	
		T3A	150	150	330/132/33	MITSUBISHI	
2	OWERRI	TR1	60	60	132/33/11	LEEEC	ENUGU
		TR2	60	60	132/33	LEEEC	
		T1-MOB	40	40	132/33	PAUWELLS	
3	ABA	T1A	7.5	7.5	132/6.6	PARSON	
		T1B	60	60	132/33	LEEEC	
		T2A(MOB)	60	60	132/33	MITSUBISHI	
		T2A	60	60	132/33	ABB	
		T2B	60	60	132/33	HYUNDAI	
4	UMUAHIA	T1	40	35	132/33	STEM ITALY	
		T2	40	35	132/33	STEM ITALY	
5	P.H. MAIN	T1A	60	60	132/33	HYUNDAI	PORT HARCOURT
		T2A	60	60	132/33	LEEECE	
		T3A	60	60	132/33	ABB	
6	P.H. TOWN	T1A	60	60	132/33	FERRANTI	
		T2A	30	30	132/33	PAUWELS	
		T1B	30	30	132/33	PAUWELS	
		T2B	45	30	132/33	HYUNDI	
7	AFAM	T1A	162	162	330/132	MITSUBISHI	
		T1	30	30	132/33	HYUNDI	
		T5	64	64	132/11	SECHERON	
8	AFAM IPP	TRIO	198	64	330/132	GENTRA	
9	YENAGOA	T1	30/40	40	132/33	STEM	
		T2	30/40	40	132/33	STEM	
10	AHAODA	TR1	30/40	40	132/33	STEM	
		TR2	30/40	40	132/33	HYUNDAI	
11	ELELENWO	TR1	60	60	132/33	SIEMEN	
		TR2	60	60	132/33	SIEMEN	

	STATION	TX NOM.	TX RATING (MVA)	AVAILABLE CAPACITY (MVA)	RATING (kV)	MAKE	DISCO
12	RUMUSOI	T1	60	60	132/33	BERNZ	
		T2	60	60	132/33	BERNZ	
13	EKET	T1B	45	45	132/33	ASEA	
		T2B	60	60	132/33	ABB	
14	CALABAR	T1	60	60	132/33	ASEA	
		T2	60	60	132/33	ABB	
		T3	60	60	132/33	EMCO	
15	UYO	T1A	60	60	132/33	A.B.B.	
		T2B	60	60	132/33	A.B.B.	
		T2 59 MVA	59	59	132/33	A.B.B.	
16	ITU	T1A	60	60	132/33	LEEECE	
ABUJA REGION							
1	KATAMPE	T1	150/90	150	330/132	ABB	
		T2	150/90	150	330/133	ABB	
		T3	150/90	150	330/132	AREVA	
		T1A	60/45	60	132/33	ABB	
		T2A	60/45	60	132/33	ABB	
		TR3	100MVA	100	132/33		
2	GWAGWALADA	T1	150/90	150	330/132	ABB	
		T2	150/90	150	330/132	ABB	
		T1A	60/45	60	132/33	ABB	
		T2A	60/45	60	132/33	ABB	
3	APO T.S.	T1	45/30/20	45	132/33/11	TRAFO-UNION	
		T2	45/30/20	45	132/33/11	TRAFO-UNION	
		T3	60/45	60	132/33	ABB	
		T4	100	100	132/33	STEKO	
4	CENTRAL AREA	T1	60/45	60	132/33	ABB	
		T2	60/45	60	132/33	ABB	
		T3	60/45	60	132/33	CROMPTON GREEVES	
5	KUKWABA	TR1	60	60	132/33		
		TR2	60	60	132/33		
6	KEFFI	TR1	30	30	132/33	ABB	
		TR2	60/45	`60/45	132/33		
7	KUBWA	TR1	60	60	132/33	ABB	
		TR2	60	60	132/33	ABB	

	STATION	TX NOM.	TX RATING (MVA)	AVAILABLE CAPACITY (MVA)	RATING (kV)	MAKE	DISCO
8	AKWANGA	T1	40	40	132/33	ABB	
		T2	40	40	132/33	MOBITRA	
9	SULEJA	T1	7.5	7.5	132/11	TRAFO-UNION	
		T2	45	45	132/33	HYUNDAI	
		T3	30	30	132/33	ABB POWER TEK	
		T5	60	60	132/33		
10	KARU	TR1	60/45	60	132/33	VIJAI INDIA	
		TR2	60/45	60	132/33	VIJAI INDIA	
11	OKPELLA	T1	15	15	132/33	FERRANTI	
12	OKENE	T1	30	30	132/33	HYUNDAI	ABUJA/BENIN
		T2	30/40	40	132/33	TOSHIBA	
13	AJAOKUTA ACC	AT1	162	162	330/132/33	MITSUBISHI	
		AT2	162	162	330/132/33	MITSUBISHI	
		AT3	162	162	330/132/33	MITSUBISHI	
14	AJAOKUTA II	T1	30/20	20	132/33		
		T2	60	60	132/33		
15	LOKOJA T.S.	T1	60	60	132/33	CROMPTON GREAVE	
		T2	150	150	330/132/33	CROMPTON GREAVE	

Appendix 5

Table 15. Grid Generators (source: Fitchner, 2017)

STATION	NOM.	TYPE	MAKE	RATING (MVA)	TERMINAL VOLTAGE (kV)	RATED P.F. (pu)	X"d sat. (pu)	X"d unsat (pu)	X"q sat. (pu)	X"q unsat. (pu)	X'd sat. (pu)	X'd unsat. (pu)	X'q sat. (pu)	X'q unsat. (pu)	Xd sat. (pu)	Xd unsat. (pu)	Xq sat. (pu)	Xq unsat. (pu)	X2 sat. (pu)	X2 unsat. (pu)	X0 sat. (pu)	X0 unsat. (pu)	XL sat. (pu)	XL unsat. (pu)	Xp (pu)	Xc (pu)	R1 (pu)	R2 (pu)	R0 (pu)	Ra (m)	Rf (m)
OKPAI (AGIP)	GT11	GAS	ALSTOM	210	15.75 +/ 5%	0.85	0.14	0.19 +/- 10%		0.2		0.25+ -10%		0.4		2.53		2.36	0.15	0.19		0.086		0.17	0.25		0.0026	0.015 at 95 C	0.0011at 95 C	1.291	188
	GT12	GAS	ALSTOM	210	15.75 +/ 5%	0.85	0.14	0.19 +/- 10%		0.2		0.25+ -10%		0.4		2.53		2.36	0.15	0.19		0.086		0.17	0.25		0.0026	0.015 at 95 C	0.0011at 95 C	1.291	188
	ST18	STEAM		210	15.75 +/ 5%	0.85	0.14	0.19 +/- 10%		0.2		0.25+ -10%		0.4		2.53		2.36	0.15	0.19		0.086		0.17	0.25		0.0026	0.015 at 95 C	0.0011at 95 C	1.291	188
DELTA I	GT1	GAS		45																											
	GT2	GAS		45																											
DELTA II	GT3	GAS	MEIDEN	29.725	11.5 +/ 5%	0.8	0.13	0.15			0.19	0.21			1.59	1.8															
	GT4	GAS	MEIDEN	29.725	11.5 +/ 5%	0.8	0.13	0.15			0.19	0.21			1.59	1.8															
	GT5	GAS	MEIDEN	29.725	11.5 +/ 5%	0.8	0.13	0.15			0.19	0.21			1.59	1.8															
	GT6	GAS	MEIDEN	29.725	11.5 +/ 5%	0.8	0.13	0.15			0.19	0.21			1.59	1.8															
	GT7	GAS	SIEMENS	29.725	11.5 +/ 5%	0.8	0.105	0.129	0.115	0.142	0.151	0.168	0.283	0.313	1.34	1.44	1.16	1.37	0.11	0.136	0.096	0.07		0.105						8.46	93.01
	GT8	GAS	SIEMENS	29.725	11.5 +/ 5%	0.8	0.105	0.129	0.115	0.142	0.151	0.168	0.283	0.313	1.34	1.44	1.16	1.37	0.11	0.136	0.096	0.07		0.105						8.46	93.01
DELTA III	GT9	GAS	SIEMENS	29.725	11.5 +/ 5%	0.8	0.105	0.129	0.115	0.142	0.151	0.168	0.283	0.313	1.34	1.44	1.16	1.37	0.11	0.136	0.096	0.07		0.105						8.46	93.01
	GT10	GAS	SIEMENS	29.725	11.5 +/ 5%	0.8	0.105	0.129	0.115	0.142	0.151	0.168	0.283	0.313	1.34	1.44	1.16	1.37	0.11	0.136	0.096	0.07		0.105						8.46	93.01
	GT11	GAS	SIEMENS	29.725	11.5 +/ 5%	0.8	0.105	0.129	0.115	0.142	0.151	0.168	0.283	0.313	1.34	1.44	1.16	1.37	0.11	0.136	0.096	0.07		0.105						8.46	93.01
	GT12	GAS	SIEMENS	29.725	11.5 +/ 5%	0.8	0.105	0.129	0.115	0.142	0.151	0.168	0.283	0.313	1.34	1.44	1.16	1.37	0.11	0.136	0.096	0.07		0.105						8.46	93.01
	GT13	GAS	SIEMENS	29.725	11.5 +/ 5%	0.8	0.105	0.129	0.115	0.142	0.151	0.168	0.283	0.313	1.34	1.44	1.16	1.37	0.11	0.136	0.096	0.07		0.105						8.46	93.01
	GT14	GAS	SIEMENS	29.725	11.5 +/ 5%	0.8	0.105	0.129	0.115	0.142	0.151	0.168	0.283	0.313	1.34	1.44	1.16	1.37	0.11	0.136	0.096	0.07		0.105						8.46	93.01
DELTA IV	GT15	GAS	GE	133.75	11.5 +/ 5%	0.85	0.171	0.226	0.166	0.223	0.241	0.319	0.542	0.542	1.905	1.905	1.835	1.835	0.161	0.214	0.077	0.096		0.181			0.004	0.018	0.007	0.004	0.016
	GT16	GAS	GE	133.75	11.5 +/ 5%	0.85	0.171	0.226	0.166	0.223	0.241	0.319	0.542	0.542	1.905	1.905	1.835	1.835	0.161	0.214	0.077	0.096		0.181			0.004	0.018	0.007	0.004	0.016
	GT17	GAS	GE	133.75	11.5 +/ 5%	0.85	0.171	0.226	0.166	0.223	0.241	0.319	0.542	0.542	1.905	1.905	1.835	1.835	0.161	0.214	0.077	0.096		0.181			0.004	0.018	0.007	0.004	0.016
	GT18	GAS	GE	133.75	11.5 +/ 5%	0.85	0.171	0.226	0.166	0.223	0.241	0.319	0.542	0.542	1.905	1.905	1.835	1.835	0.161	0.214	0.077	0.096		0.181			0.004	0.018	0.007	0.004	0.016

STATION	NOM.	TYPE	MAKE	RATING (MVA)	TERMINAL VOLTAGE (kV)	RATED P.F. (pu)	X"d sat. (pu)	X"d unsat. (pu)	X"q sat. (pu)	X"q unsat. (pu)	X'd sat. (pu)	X'd unsat. (pu)	X'q sat. (pu)	X'q unsat. (pu)	Xd sat. (pu)	Xd unsat. (pu)	Xq sat. (pu)	Xq unsat. (pu)	X2 sat. (pu)	X2 unsat. (pu)	X0 sat. (pu)	X0 unsat. (pu)	XL sat. (pu)	XL unsat. (pu)	Xp (pu)	Xc (pu)	R1 (pu)	R2 (pu)	R0 (pu)	Ra (m)	Rf (m)
	GT19	GAS	GE	133.75	11.5 +/ 5%	0.85	0.171	0.226	0.166	0.223	0.241	0.319	0.542	0.542	1.905	1.905	1.835	1.835	0.161	0.214	0.077	0.096		0.181			0.004	0.018	0.007	0.004	0.016
	GT20	GAS	GE	133.75	11.5 +/ 5%	0.85	0.171	0.226	0.166	0.223	0.241	0.319	0.542	0.542	1.905	1.905	1.835	1.835	0.161	0.214	0.077	0.096		0.181			0.004	0.018	0.007	0.004	0.016
SAPELE	ST1	STEAM	BBC	133.97	15.75 +/ 5%	0.9	0.16	0.16			0.2	0.215			1.77	2.4				0.164		0.087		0.13	0.322					2.21	
SAPELE	ST2	STEAM	BBC	133.97	15.75 +/ 5%	0.9	0.16	0.16			0.2	0.215			1.77	2.4				0.164		0.087		0.13	0.322					2.21	
SAPELE	ST3	STEAM	BBC	133.97	15.75 +/ 5%	0.9	0.16	0.16			0.2	0.215			1.77	2.4				0.164		0.087		0.13	0.322					2.21	
SAPELE	ST4	STEAM	BBC	133.97	15.75 +/ 5%	0.9	0.16	0.16			0.2	0.215			1.77	2.4				0.164		0.087		0.13	0.322					2.21	
SAPELE	ST5	STEAM	BBC	133.97	15.75 +/ 5%	0.9	0.16	0.16			0.2	0.215			1.77	2.4				0.164		0.087		0.13	0.322					2.21	
SAPELE	ST6	STEAM	BBC	133.97	15.75 +/ 5%	0.9	0.16	0.16			0.2	0.215			1.77	2.4				0.164		0.087		0.13	0.322					2.21	
SAPELE	GT1	GAS	BBC	110	10.5+ / 7.5%	0.8	0.133	0.154			0.2	0.21			1.77	2.17						0.083		0.13	0.13					0.92	
SAPELE	GT2	GAS	BBC	110	10.5+ / 7.5%	0.8	0.133	0.154			0.2	0.21			1.77	2.17						0.083		0.13	0.13					0.92	
SAPELE	GT3	GAS	BBC	110	10.5+ / 7.5%	0.8	0.133	0.154			0.2	0.21			1.77	2.17						0.083		0.13	0.13					0.92	
SAPELE	GT4	GAS	BBC	110	10.5+ / 7.5%	0.8	0.133	0.154			0.2	0.21			1.77	2.17						0.083		0.13	0.13					0.92	
EGBIN	ST1	STEAM	HITACHI	245.8	16	0.9	0.23	0.28	0.23	0.28	0.26	0.31	0.45	0.5	1.87	2	1.87	2		0.23		0.16	0.2	0.15	0.25	0.102	0.401 at 95 C	5.72 at 95 C	8.09 at 95 C		
EGBIN	ST2	STEAM	HITACHI	245.8	16	0.9	0.23	0.28	0.23	0.28	0.26	0.31	0.45	0.5	1.87	2	1.87	2		0.23		0.16	0.2	0.15	0.25	0.102	0.401 at 95 C	5.72 at 95 C	8.09 at 95 C		
EGBIN	ST3	STEAM	HITACHI	245.8	16	0.9	0.23	0.28	0.23	0.28	0.26	0.31	0.45	0.5	1.87	2	1.87	2		0.23		0.16	0.2	0.15	0.25	0.102	0.401 at 95 C	5.72 at 95 C	8.09 at 95 C		
EGBIN	ST4	STEAM	HITACHI	245.8	16	0.9	0.23	0.28	0.23	0.28	0.26	0.31	0.45	0.5	1.87	2	1.87	2		0.23		0.16	0.2	0.15	0.25	0.102	0.401 at 95 C	5.72 at 95 C	8.09 at 95 C		
EGBIN	ST5	STEAM	HITACHI	245.8	16	0.9	0.23	0.28	0.23	0.28	0.26	0.31	0.45	0.5	1.87	2	1.87	2		0.23		0.16	0.2	0.15	0.25	0.102	0.401 at 95 C	5.72 at 95 C	8.09 at 95 C		
EGBIN	ST6	STEAM	HITACHI	245.8	16	0.9	0.23	0.28	0.23	0.28	0.26	0.31	0.45	0.5	1.87	2	1.87	2		0.23		0.16	0.2	0.15	0.25	0.102	0.401 at 95 C	5.72 at 95 C	8.09 at 95 C		
AES	GT 1	GAS	GEC ALSTOM	38.6	10.5	0.8	0.105				0.2				1.76		1.62						0.105								
AES	GT 2	GAS	GEC ALSTOM	38.6	10.5	0.8	0.105				0.2				1.76		1.62						0.105								
AES	GT 3	GAS	GEC ALSTOM	38.6	10.5	0.8	0.105				0.2				1.76		1.62						0.105								
AES	GT 4	GAS	JOHN BROWN	39.54	10.5	0.8	0.105				0.2				1.76		1.62						0.105								
AES	GT 5	GAS	JOHN BROWN	39.54	10.5	0.8	0.105				0.2				1.76		1.62						0.105								
AES	GT 6	GAS	JOHN BROWN	39.54	10.5	0.8	0.105				0.2				1.76		1.62						0.105								
AES	GT 7	GAS	IUKA	40.5	10.5	0.9	0.105				0.2				1.76		1.62						0.105								

STATION	NO M.	TYPE	MAKE	RATING (MVA)	TERMINAL VOLTAGE (kV)	RATED P.F. (pu)	X"d sat. (pu)	X"d unsat (pu)	X"q sat. (pu)	X"q unsat. (pu)	X'd sat. (pu)	X'd unsat. (pu)	X'q sat. (pu)	X'q unsat. (pu)	Xd sat. (pu)	Xd unsat. (pu)	Xq sat. (pu)	Xq unsat. (pu)	X2 sat. (pu)	X2 unsat. (pu)	X0 sat. (pu)	X0 unsat. (pu)	XL sat. (pu)	XL unsat. (pu)	Xp (pu)	Xc (pu)	R1 (pu)	R2 (pu)	R0 (pu)	Ra (m)	Rf (m)
	GT 8	GAS	IUKA	40.5	10.5	0.9	0.105				0.2				1.76		1.62						0.105								
	GT 9	GAS	IUKA	40.5	10.5	0.9	0.105				0.2				1.76		1.62						0.105								
JEBBA	2G1	HYDRO	HITACHI	119	16	0.85	0.26	0.24	0.24	0.24		0.26				0.65	0.69	0.48	0.24	0.24	0.15	0.15	0.24		0.14					9.2	19
	2G2	HYDRO	HITACHI	119	16	0.85	0.26	0.24	0.24	0.24		0.26				0.65	0.69	0.48	0.24	0.24	0.15	0.15	0.24		0.14					9.2	19
	2G3	HYDRO	HITACHI	119	16	0.85	0.26	0.24	0.24	0.24		0.26				0.65	0.69	0.48	0.24	0.24	0.15	0.15	0.24		0.14					9.2	19
	2G4	HYDRO	HITACHI	119	16	0.85	0.26	0.24	0.24	0.24		0.26				0.65	0.69	0.48	0.24	0.24	0.15	0.15	0.24		0.14					9.2	19
	2G5	HYDRO	HITACHI	119	16	0.85	0.26	0.24	0.24	0.24		0.26				0.65	0.69	0.48	0.24	0.24	0.15	0.15	0.24		0.14					9.2	19
	2G6	HYDRO	HITACHI	119	16	0.85	0.26	0.24	0.24	0.24		0.26				0.65	0.69	0.48	0.24	0.24	0.15	0.15	0.24		0.14					9.2	19
KAINJI	1G5	HYDRO	HITACHI	126	16	0.95	0.22		0.22		0.3				0.85		0.55		0.22	0.16	0.19	0.19	0.155							6	175
	1G6	HYDRO	HITACHI	126	16	0.95	0.22		0.22		0.3				0.85		0.55		0.22	0.16	0.19	0.19	0.155							6	175
	1G7	HYDRO	ASEA	85	16	0.95	0.17		0.22		0.248				0.76		0.46		0.22		0.19	0.19	0.104							6	19
	1G8	HYDRO	ASEA	85	16	0.95	0.17		0.22		0.248				0.76		0.46		0.22		0.19	0.19	0.104							6	19
	1G9	HYDRO	ASEA	85	16	0.95	0.17		0.22		0.248				0.76		0.46		0.22		0.19	0.19	0.104							6	19
	1G10	HYDRO	ASEA	85	16	0.95	0.17		0.22		0.248				0.76		0.46		0.22		0.19	0.19	0.104							6	19
	1G11	HYDRO	HITACHI	115	16	0.95	0.2		0.22		0.26				0.72		0.5		0.21		0.14	0.14	0.129							9	19
	1G12	HYDRO	HITACHI	115	16	0.95	0.2		0.22		0.26				0.72		0.5		0.21		0.14	0.14	0.129							9	19
SHIRORO	411G1	HYDRO	RADE KONCAR	176.5	15.65	0.85	0.2	0.2	0.24	0.24	0.3	0.3	0.24	0.24	0.8	0.8	0.49	0.49	0.22	0.22	0.11	0.11	0.15		0.16	0.15					
	411G2	HYDRO	RADE KONCAR	176.5	15.65	0.85	0.2	0.2	0.24	0.24	0.3	0.3	0.24	0.24	0.8	0.8	0.49	0.49	0.22	0.22	0.11	0.11	0.15		0.16	0.15					
	411G3	HYDRO	RADE KONCAR	176.5	15.65	0.85	0.2	0.2	0.24	0.24	0.3	0.3	0.24	0.24	0.8	0.8	0.49	0.49	0.22	0.22	0.11	0.11	0.15		0.16	0.15					
	411G4	HYDRO	RADE KONCAR	176.5	15.65	0.85	0.2	0.2	0.24	0.24	0.3	0.3	0.24	0.24	0.8	0.8	0.49	0.49	0.22	0.22	0.11	0.11	0.15		0.16	0.15					
AFAM I	GT1	GAS	BBC	16	10.5 ±7.5	0.8		0.13				0.18				1.27		1.143													
	GT2	GAS	BBC	16	10.5 ±7.5	0.8		0.13				0.18				1.27		1.143													
	GT3	GAS	BBC	25	10.5 ±7.5	0.8		0.13				0.19				1.3		1.17													
	GT4	GAS	BBC	25	10.5 ±7.5	0.8		0.13				0.19				1.3		1.17													
AFAM II	GT5	GAS	BBC	30	10.5 ±7.5	0.8	0.105	0.12				0.21	0.3		1.59	2.25	1.37	2.025					0.105								
	GT6	GAS	BBC	30	10.5 ±7.5	0.8	0.105	0.12				0.21	0.3		1.59	2.25	1.37	2.025					0.105								
	GT7	GAS	BBC	30	10.5 ±7.5	0.8	0.105	0.12				0.21	0.3		1.59	2.25	1.37	2.025					0.105								

STATION	NOM.	TYPE	MAKE	RATING (MVA)	TERMINAL VOLTAGE (kV)	RATED P.F. (pu)	X"d sat. (pu)	X"d unsat. (pu)	X"q sat. (pu)	X"q unsat. (pu)	X'd sat. (pu)	X'd unsat. (pu)	X'q sat. (pu)	X'q unsat. (pu)	Xd sat. (pu)	Xd unsat. (pu)	Xq sat. (pu)	Xq unsat. (pu)	X2 sat. (pu)	X2 unsat. (pu)	X0 sat. (pu)	X0 unsat. (pu)	XL sat. (pu)	XL unsat. (pu)	Xp (pu)	Xc (pu)	R1 (pu)	R2 (pu)	R0 (pu)	Ra (m)	Rf (m)
	GT8	GAS	BBC	30	10.5 ±7.5	0.8	0.105	0.12				0.21	0.3		1.59	2.25	1.37	2.025					0.105								
AFAM III	GT9	GAS	BBC	34	10.5 ±7.5	0.8		0.12				0.15				2.09		1.881													
	GT10	GAS	BBC	34	10.5 ±7.5	0.8		0.12				0.15				2.09		1.881													
	GT11	GAS	BBC	34	10.5 ±7.5	0.8		0.12				0.15				2.09		1.881													
	GT12	GAS	BBC	34	10.5 ±7.5	0.8		0.12				0.15				2.09		1.881													
AFAM IV	GT13	GAS	BBC	110	10.5 ±7.5	0.8		0.154				0.21				2.17						0.132		0.088							
	GT14	GAS	BBC	110	10.5 ±7.5	0.8		0.154				0.21				2.17						0.132		0.088							
	GT15	GAS	BBC	110	11.5± 5	0.8		0.137				0.211				2.37						0.152		0.081							
AFAM IV	GT16	GAS	BBC	110	11.5± 5	0.8		0.137				0.211				2.37						0.152		0.081							
	GT17	GAS	BBC	110	11.5± 5	0.8	0.133	0.137			0.21	0.211			2.17	2.37	1.95					0.152	0.13	0.081							
	GT18	GAS	BBC	110	11.5± 5	0.8	0.133	0.137			0.21	0.211			2.17	2.37	1.95					0.152	0.13	0.081							
AFAM V	GT19	GAS	SIEMENS	162.69	15.75 ± 5	0.85	0.2				0.275				2.3		2.2						0.175								
	GT20	GAS	SIEMENS	162.69	15.75 ± 5	0.85	0.2				0.275				2.3		2.2						0.175								
PAPALANTO (OLORUNSOGO)	GT1	GAS	GE (FRAME 6)	48	10.5	0.8	0.148				0.22				2.47	2		2		0.19		0.095				0.137	0.0036 at 20 C	0.132 at 20 C			
	GT2	GAS	GE (FRAME 6)	48	10.5	0.8	0.148				0.22				2.47	2		2		0.19		0.095				0.137	0.0036 at 20 C	0.132 at 20 C			
	GT3	GAS	GE (FRAME 6)	48	10.5	0.8	0.148				0.22				2.47	2		2		0.19		0.095				0.137	0.0036 at 20 C	0.132 at 20 C			
	GT4	GAS	GE (FRAME 6)	48	10.5	0.8	0.148				0.22				2.47	2		2		0.19		0.095				0.137	0.0036 at 20 C	0.132 at 20 C			
	GT5	GAS	GE (FRAME 6)	48	10.5	0.8	0.148				0.22				2.47	2		2		0.19		0.095				0.137	0.0036 at 20 C	0.132 at 20 C			
	GT6	GAS	GE (FRAME 6)	48	10.5	0.8	0.148				0.22				2.47	2		2		0.19		0.095				0.137	0.0036 at 20 C	0.132 at 20 C			
	GT7	GAS	GE (FRAME 6)	48	10.5	0.8	0.148				0.22				2.47	2		2		0.19		0.095				0.137	0.0036 at 20 C	0.132 at 20 C			
	GT8	GAS	GE (FRAME 6)	48	10.5	0.8	0.148				0.22				2.47	2		2		0.19		0.095				0.137	0.0036 at 20 C	0.132 at 20 C			
OMOTOSO PHASE I	GT1	GAS	NANJING	47.5	10.5+ / 5%	0.8		0.17		0.17		0.231	0.231			2.38		2.38		0.1941		0.103		0.137						3.84	138.8
	GT2	GAS	NANJING	47.5	10.5+ / 5%	0.8		0.17		0.17		0.231	0.231			2.38		2.38		0.1941		0.103		0.137						3.84	138.8
	GT3	GAS	NANJING	47.5	10.5+ / 5%	0.8		0.17		0.17		0.231	0.231			2.38		2.38		0.1941		0.103		0.137						3.84	138.8
	GT4	GAS	NANJING	47.5	10.5+ / 5%	0.8		0.17		0.17		0.231	0.231			2.38		2.38		0.1941		0.103		0.137						3.84	138.8
	GT5	GAS	NANJING	47.5	10.5+ / 5%	0.8		0.17		0.17		0.231	0.231			2.38		2.38		0.1941		0.103		0.137						3.84	138.8

STATION	NOM.	TYPE	MAKE	RATING (MVA)	TERMINAL VOLTAGE (kV)	RATED P.F. (pu)	X"d sat. (pu)	X"d unsat. (pu)	X"q sat. (pu)	X"q unsat. (pu)	X'd sat. (pu)	X'd unsat. (pu)	X'q sat. (pu)	X'q unsat. (pu)	Xd sat. (pu)	Xd unsat. (pu)	Xq sat. (pu)	Xq unsat. (pu)	X2 sat. (pu)	X2 unsat. (pu)	X0 sat. (pu)	X0 unsat. (pu)	XL sat. (pu)	XL unsat. (pu)	Xp (pu)	Xc (pu)	R1 (pu)	R2 (pu)	R0 (pu)	Ra (m)	Rf (m)
	GT6	GAS	NANJING	47.5	10.5+/ 5%	0.8		0.17		0.17		0.231	0.231			2.38		2.38		0.1941		0.103		0.137						3.84	138.8
	GT7	GAS	NANJING	47.5	10.5+/ 5%	0.8		0.17		0.17		0.231	0.231			2.38		2.38		0.1941		0.103		0.137						3.84	138.8
	GT8	GAS	NANJING	47.5	10.5+/ 5%	0.8		0.17		0.17		0.231	0.231			2.38		2.38		0.1941		0.103		0.137						3.84	138.8
GEREGU	GT11	GAS	SIEMENS	174	15.75+/ 5%	0.85	0121+/ 15%				0.184+/ 15%					1.918+/ 15%											0.0039		0.0062	5	
	GT12	GAS	SIEMENS	174	15.75+/ 5%	0.85	0121+/ 15%				0.184+/ 15%					1.918+/ 15%											0.0039		0.0062	5	
	GT13	GAS	SIEMENS	174	15.75+/ 5%	0.85	0121+/ 15%				0.184+/ 15%					1.918+/ 15%											0.0039		0.0062	5	
ALAOJI (NIPP)	GT1	GAS	GE	141.25	15	0.85	0.132	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027 at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
	GT2	GAS	GE	141.25	15	0.85	0.132	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
	GT3	GAS	GE	141.25	15	0.8	0.132	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
	GT4	GAS																													
CALABAR (ODUKPANI)	GT1	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
	GT2	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
	GT3	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
	GT4	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
	GT5	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
EGBEMA	UNIT1	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
	UNIT2	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
	UNIT3	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
EYAEN (IHOVBOR)	GT1	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
	GT2	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
	GT3	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
	GT4	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
GBARAIN	GT1	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
	GT2	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
IKOT ABASI	UNIT1	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
	UNIT2	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
	UNIT3	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93

STATION	NO M.	TYPE	MAKE	RATING (MVA)	TERMINAL VOLTAGE (kV)	RATED P.F. (pu)	X"d sat. (pu)	X"d unsat (pu)	X"q sat. (pu)	X"q unsat. (pu)	X'd sat. (pu)	X'd unsat. (pu)	X'q sat. (pu)	X'q unsat. (pu)	Xd sat. (pu)	Xd unsat. (pu)	Xq sat. (pu)	Xq unsat. (pu)	X2 sat. (pu)	X2 unsat. (pu)	X0 sat. (pu)	X0 unsat. (pu)	XL sat. (pu)	XL unsat. (pu)	Xp (pu)	Xc (pu)	R1 (pu)	R2 (pu)	R0 (pu)	Ra (m)	Rf (m)
OMOKU	GT1	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
	GT2	GAS	GE	141.25	15	0.8	0.13	0.164	0.16	0.195	0.19	0.231	0.23	0.33		1.82	1.35	1.66	0.129	0.16		0.08	0.078	0.119	0.196		0.0027at 75 C	0.0188at 75 C	0.0041at 75 C	1.2	93
	GT3	GAS	GE																												
	GT4	GAS	GE																												
	GT5	GAS	GE																												
	GT6	GAS	GE																												
GEREGU (NIPP)	GT21	GAS		148 MW																											
	GT22	GAS		148 MW																											
	GT23	GAS		148 MW																											
OMOTOSO (NIPP)	GT1	GAS	ALSTOM	165	15	0.8	0.168	0.195			0.26	0.267				2.295						0.102								1.84	
	GT2	GAS	ALSTOM	165	15	0.8	0.168	0.195			0.26	0.267				2.295						0.102								1.84	
	GT3	GAS	ALSTOM	165	15	0.8	0.168	0.195			0.26	0.267				2.295						0.102								1.84	
	GT4	GAS	ALSTOM	165	15	0.8	0.168	0.195			0.26	0.267				2.295						0.102								1.84	
PAPALANTO (OLORUNSOGO NIPP)	GT1	GAS	ALSTOM	157.954	15	0.8	0.161	0.187			0.249	0.256				2.197			0.161	0.197		0.098					0.255			1.84	
	GT2	GAS	ALSTOM	157.954	15	0.8	0.161	0.187			0.249	0.256				2.197			0.161	0.197		0.098					0.255			1.84	
	GT3	GAS	ALSTOM	157.954	15	0.8	0.161	0.187			0.249	0.256				2.197			0.161	0.197		0.098					0.255			1.84	
	GT4	GAS	ALSTOM	157.954	15	0.8	0.161	0.187			0.249	0.256				2.197			0.161	0.197		0.098					0.255			1.84	
	ST13	STEAM																													
	ST23	STEAM																													
AFAM VI (SHELL)	GT11	GAS	ALSTOM	195	15.75	0.85		0.174		0.187		0.231		0.374		2.35		2.188		0.178		0.08					0.0024	0.0136	0.00101	1.291	187.8
	GT12	GAS	ALSTOM	195	15.75	0.85		0.174		0.187		0.231		0.374		2.35		2.188		0.178		0.08					0.0024	0.0136	0.00101	1.291	187.8
	GT13	GAS	ALSTOM	195	15.75	0.85		0.174		0.187		0.231		0.374		2.35		2.188		0.178		0.08					0.0024	0.0136	0.00101	1.291	187.8
	ST10	STEAM	ALSTOM	270	19	0.85	0.11	0.155	0.116	0.166	0.18	0.201	0.299	0.332		1.947		1.83	0.115	0.158	0.06	0.086		0.139	0.215	0.562	0.00176	0.0115	0.00078	1.046	228.8
ASCO	ST1																														
BONNY (MOBIL)				130 MW																											
				130 MW																											

STATION	NOM.	TYPE	MAKE	RATING (MVA)	TERMINAL VOLTAGE (kV)	RATED P.F. (pu)	X"d sat. (pu)	X"d unsat (pu)	X"q sat. (pu)	X"q unsat. (pu)	X'd sat. (pu)	X'd unsat. (pu)	X'q sat. (pu)	X'q unsat. (pu)	Xd sat. (pu)	Xd unsat. (pu)	Xq sat. (pu)	Xq unsat. (pu)	X2 sat. (pu)	X2 unsat. (pu)	X0 sat. (pu)	X0 unsat. (pu)	XL sat. (pu)	XL unsat. (pu)	Xp (pu)	Xc (pu)	R1 (pu)	R2 (pu)	R0 (pu)	Ra (m)	Rf (m)
				130 MW																											
CHEVRON TEXACO				250 MW																											
				250 MW																											
				250 MW																											
TOTALFINAELF (1&2)				125 MW																											
				125 MW																											
				125 MW																											
				125 MW																											
				90 MW																											
				90 MW																											
				90 MW																											
				90 MW																											
IBOM POWER I	GTG-1	GAS	GE (FRAME 6)	48	10.5	0.8	0.148				0.22				2.47	2		2		0.19		0.095				0.137	0.0036 at 20 C	0.132 at 20 C			
	GTG-2	GAS	GE (FRAME 6)	48	10.5	0.8	0.148				0.22				2.47	2		2		0.19		0.095				0.137	0.0036 at 20 C	0.132 at 20 C			
	GTG-3	GAS	ALSTOM) BRUS	141.25	15	0.8		0.16		0.195	0.1302	0.231		0.33		1.81		1.664	0.1966	0.16		0.0798					0.00273	0.01877	0.0041		
IBOM POWER II				504 MW																											

Appendix 6

Table 16. Generation System Transformers (source: NIPP, 2007)

STATION	NOMEN-CLATURE	RATING		COOLING	VECTOR GROUP
		POWER (MVA)	VOLTAGE (kV)		
DELTA	T4	54/72/81	138/11.5/11.5/11.5	OA/FA/FA	Yd
	T5	45/81	138/11.5/11.5/11.5	ONAN/ONAF	YNddd1
	T6	54/72/81	138/11.5/11.5/11.5	OA/FA/FA	YNddd1
DELTA IV	GT15	72/96/120	345/11.5	ONAN/ONAF/ONAF	YNd1
	GT16	72/96/120	345/11.5	ONAN/ONAF/ONAF	YNd1
	GT17	72/96/120	345/11.5	ONAN/ONAF/ONAF	YNd1
	GT18	72/96/120	345/11.5	ONAN/ONAF/ONAF	YNd1
	GT19	72/96/120	345/11.5	ONAN/ONAF/ONAF	YNd1
	GT20	72/96/120	345/11.5	ONAN/ONAF/ONAF	YNd1
DELTA	Interbus	90/120/150	330/132	ONAN/ONAF/ONAF	YNa0d1
SAPELE	T1	90/140	345/15.75	ONAN/ONAF	YNd1
	T2	90/140	345/15.75	ONAN/ONAF	YNd1
	T3	90/140	345/15.75	ONAN/ONAF	YNd1
	T6	90/140	345/15.75	ONAN/ONAF	YNd1
	T4	105/140	345/15.75	ONAN/ONAF	YNd1
	T5	105/140	345/15.75	ONAN/ONAF	YNd1
	T9	126/168.5	345/10.5	ONAN/ONAF	YNd1d1
	T10	126/168.5	345/10.5	ONAN/ONAF	YNd1d1
OKPAI	GT1	140/205	330/15.75	ONAN/ONAF	YNd11
	GT2	140/205	330/15.75	ONAN/ONAF	YNd11
	GT3	140/205	330/15.75	ONAN/ONAF	YNd11
	GT4	140/205	330/15.75	ONAN/ONAF	YNd11
AFAM PS	GT13	109/168	10.5/345	ONAN/ONAF	YNd1/d1
	GT14	109/168	10.5/345	ONAN/ONAF	YNd1/d1
	GT15	109/168	10.5/345	ONAN/ONAF	YNd1/d1
	GT16	109/168	10.5/345	ONAN/ONAF	YNd1/d1
	GT17	109/168	10.5/345	ONAN/ONAF	YNd1/d1
	GT18	109/168	10.5/345	ONAN/ONAF	YNd1/d1
	GT19	163	15.7/345	ODAF	YNd11
	GT20	163	15.7/345	ODAF	YNd11
	Interbus	162	330/132	ONAN/ONAF	
JEBBA GS	T1	119	16/330	ODWF	YNd1
	T2	119	16/330	ODWF	YNd1
	T3	119	16/330	ODWF	YNd1
	T4	119	16/330	ODWF	YNd1
	T5	119	16/330	ODWF	YNd1

STATION	NOMEN-CLATURE	RATING		COOLING	VECTOR GROUP
		POWER (MVA)	VOLTAGE (kV)		
	T6	119	16/330	ODWF	YNd1
KAINJI GS	T5	145	16/330	FOW	YNd1
	T6	145	16/330	FOW	YNd1
	T7	184	16/330	OFAF	YNd1
	T8	184	16/330	OFAF	YNd1
	T9	183.6	16/330	OFW	YNd1
	T10	183.6	16/330	OFW	YNd1
	T11	115	16/330	FOW	YNd1
	T12	115	16/330	FOW	YNd1
SHIRORO GS	411G1	200	15.2/330	OFWF	YNd1
	411G2	200	15.2/330	OFWF	YNd1
	411G3	200	15.2/330	OFWF	YNd1
	411G4	200	15.2/330	OFWF	YNd1
EGBIN GS	GT1	270	16/330	ONAN/ONAF	YNd1
	GT2	270	16/330	ONAN/ONAF	YNd1
	GT3	270	16/330	ONAN/ONAF	YNd1
	GT4	270	16/330	ONAN/ONAF	YNd1
	GT5	270	16/330	ONAN/ONAF	YNd1
	GT6	270	16/330	ONAN/ONAF	YNd1
	Interbus 1	150	330/132/33	ONAN/OFAF	YyOd1
AES	GT1	60	10.5/132	ONAN/ONAF	YNd1
	GT2	40	11.5/132	ONAN/ONAF	YNd1
	GT3	40	11.5/132	ONAN/ONAF	YNd1
	GT4	40	11.5/132	ONAN/ONAF	YNd1
GEREGU	GT1	168	345/15.75	ODAF	YNd11
	GT2	168	345/15.75	ODAF	YNd11
	GT3	168	345/15.75	ODAF	YNd11
OMOTOSHO	T1	105	346.5/10.5	ODAF	YNd1
	T2	105	346.5/10.5	ODAF	YNd1
	T3	105	346.5/10.5	ODAF	YNd1
	T4	105	346.5/10.5	ODAF	YNd1
	T5	105	346.5/10.5	ODAF	YNd1
	Interbus 2	150	330/132/33	ONAN/OFAF	YyOd1
OLORUNSOGO	GT1	346.5	10.5/330	ODAF	YNd1
	GT2	346.5	10.5/330	ODAF	YNd1
	GT3	346.5	10.5/330	ODAF	YNd1
	GT4	346.5	10.5/330	ODAF	YNd1
ALAOJI		102/136/170	15/330		
GBARAIN NIPP	GT1	90/143	139/15	ONAN/ONAF	YNd1

STATION	NOMEN-CLATURE	RATING		COOLING	VECTOR GROUP
		POWER (MVA)	VOLTAGE (kV)		
	GT2	90/143	139/15	ONAN/ONAF	YNd1
CALABAR	GT1	90/143	353/15	ONAN/ONAF	YNd1
	GT2	90/143	343/15	ONAN/ONAF	YNd1
	GT3	90/143	353/15	ONAN/ONAF	YNd1
	GT4	90/143	343/15	ONAN/ONAF	YNd1
	GT5	90/143	353/15	ONAN/ONAF	YNd1
EGBEMA	GT1	90/143	343/15	ONAN/ONAF	YNd1
	GT2	90/143	353/15	ONAN/ONAF	YNd1
	GT3	90/143	343/15	ONAN/ONAF	YNd1
IHOVBOR	GT1	90/143	353/15	ONAN/ONAF	YNd1
	GT2	90/143	343/15	ONAN/ONAF	YNd1
	GT3	90/143	353/15	ONAN/ONAF	YNd1
	GT4	90/143	343/15	ONAN/ONAF	YNd1
OKOT ABASI	T1	90/143	353/15	ONAN/ONAF	YNd1
	T2	90/143	343/15	ONAN/ONAF	YNd1
	T3	90/143	353/15	ONAN/ONAF	YNd1
SAPELE	GT1	90/143	353/15	ONAN/ONAF	YNd1
	GT2	90/143	353/15	ONAN/ONAF	YNd1
	GT3	90/143	353/15	ONAN/ONAF	YNd1
	GT4	90/143	353/15	ONAN/ONAF	YNd1
OMOKU	GT1	90/143	353/15	ONAN/ONAF	YNd1
	GT2	90/143	353/15	ONAN/ONAF	YNd1

Appendix 7

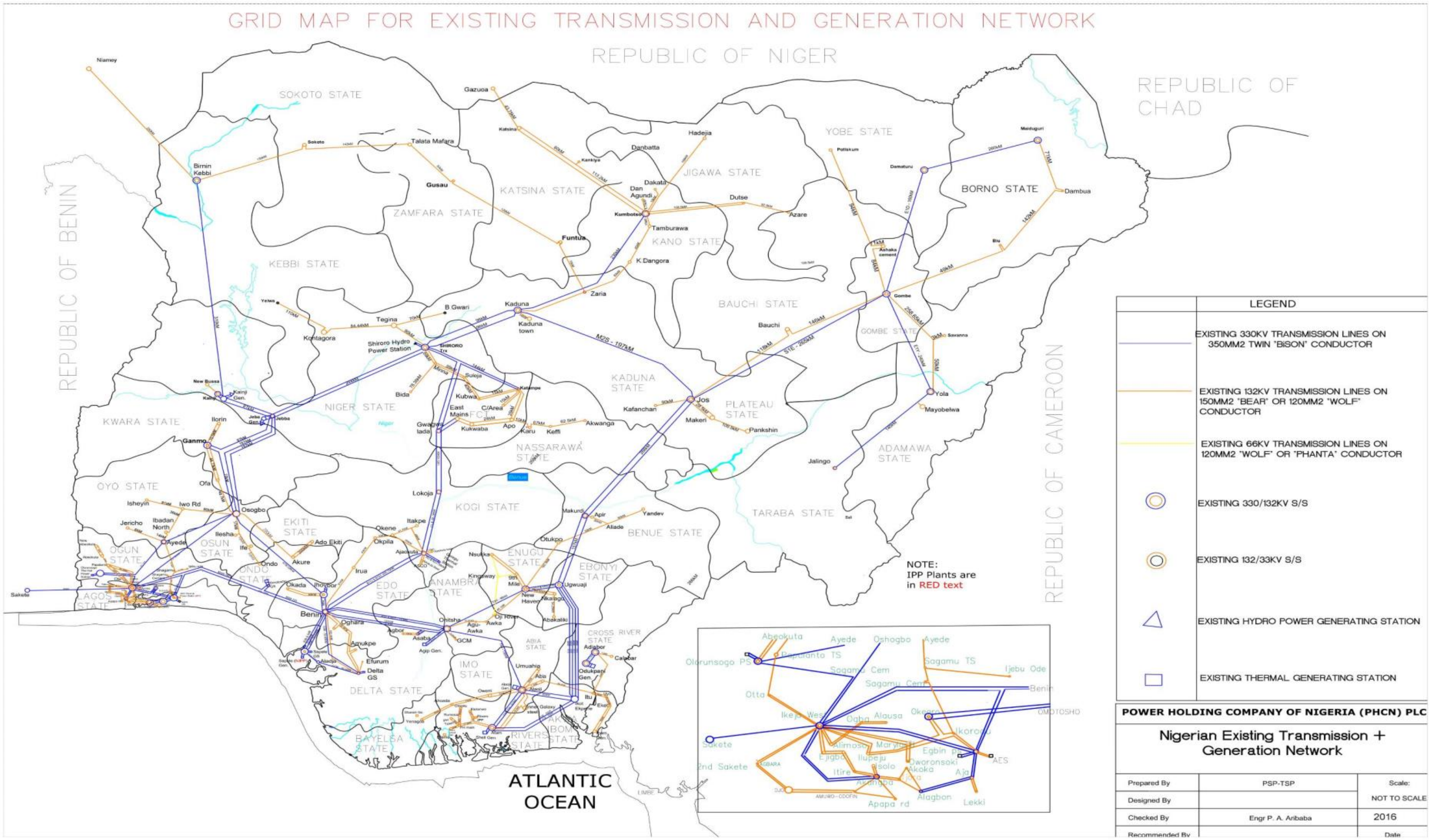


Fig. 23. Grid transmission and generation map (source: Fitchner, 2017)

Appendix 8

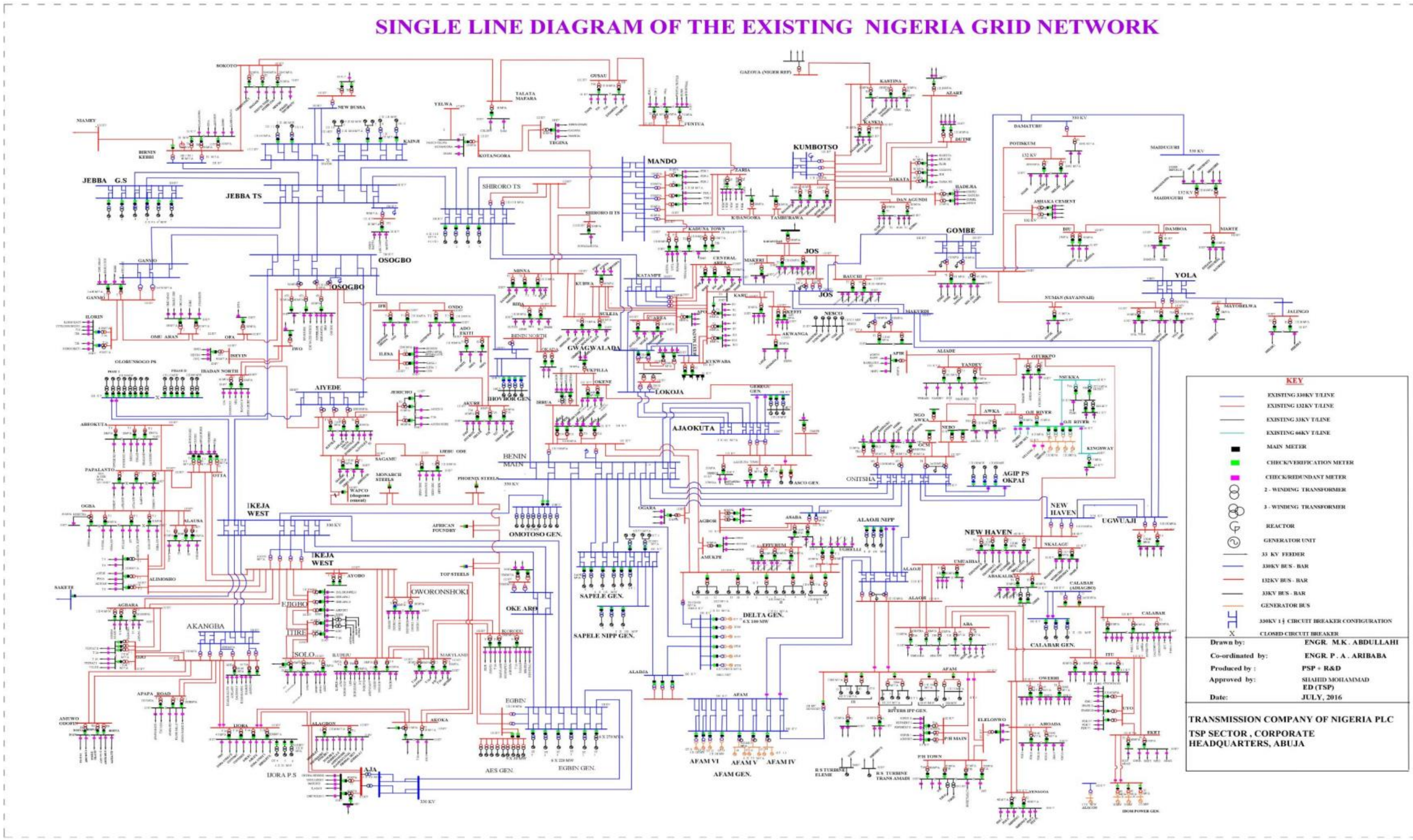


Fig. 24. Single line diagram of the grid (source: Fitchner, 2017)

RESUME

Omobolaji Oluwajuwon KOYI was born in Lagos, Nigeria in the year 1988. He graduated from Ajayi Crowther Memorial Senior Secondary School in 2005 and obtained his bachelor's degree in electrical and electronics engineering from the University of Ilorin, Nigeria in 2015. He obtained his master's degree in electrical and electronics engineering from Karadeniz Technical University, Turkey in 2019. He has benefitted from both local and international scholarships during his undergraduate and graduate education. He was awarded a master's degree scholarship by Turks Abroad and Related Communities (YTB) in 2016. He speaks Yoruba, English, and Turkish.