American Journal of Electrical Power and Energy Systems
2019; 8(5): 111-119
http://www.sciencepublishinggroup.com/j/epes
doi: 10.11648/j.epes.20190805.12
ISSN: 2326-912X (Print); ISSN: 2326-9200 (Online)

Comparative Analysis of Electrical Power Utilization in Nigeria: From Conventional Grid to Renewable Energy-based Mini-grid Systems

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To cite this article:

Unwana Macaulay Ekpe, Vincent Bassey Umoh. Comparative Analysis of Electrical Power Utilization in Nigeria: From Conventional Grid to Renewable Energy-based Mini-grid Systems. *American Journal of Electrical Power and Energy Systems.* Vol. 8, No. 5, 2019, pp. 111-119. doi: 10.11648/j.epes.20190805.12

Received: August 15, 2019; **Accepted**: September 4, 2019; **Published**: September 30, 2019

Abstract: The electrical power grid in Nigeria is limited in terms of reach and utilization, and this leaves a large section of the population without access to power supply. This paper therefore reviews literature on the current state of the conventional electrical power grid in Nigeria. The generation, transmission and distribution sectors of the grid are briefly reviewed before examining the extent, capacity and power generation technologies used by some currently deployed mini-grid systems. It is observed that a majority of deployed mini-grid systems depend on solar photovoltaic renewable energy sources and such systems are mostly isolated from the conventional grid. Therefore, to make a case for improved access to electrical power supply in the country, statistical and demographic analysis has been carried out to reveal the size of the electrical energy market available to mini-grids and the need to integrate current and future mini-grids to the conventional grid. It is noted that with substantial but targeted investments, a number of existing smart grid technologies can be employed to integrate mini-grids to the conventional grid thereby providing affordable access to electricity for communities that are hitherto unserved or underserved by the conventional grid. Some of the available smart grid technologies that have been identified to be suitable for integration purposes include advanced metering infrastructure (AMI), flexible alternating current transmission system (FACTS) and high voltage direct current (HVDC) transmission lines. A top-level schematic of how and where such technologies can be deployed is provided.

Keywords: Electrical Power, Integration, Mini-Grid, Smart Grid

1. Introduction

Electricity is vital for the development of any nation as it plays an important role in areas ranging from the provision of health, financial, agricultural and educational services to the production of industrial and consumer goods and services. Even though Nigeria has been rated as having the largest economy in Africa, the country still suffers from the problem of inadequate electrical power supply. Nigeria is blessed with vast reserves of fossil fuel and this serves as her primary source of electric power generation, which if well utilized should be adequate to supply its population of over 190 million people [1] with electricity. However, the reality is that only about 59.3% of its populations have access to both fossil fuel-sourced and renewable energy-derived electricity [2-3]. For example, some studies such as [4] shows that Nigeria has an installed generating capacity of about 12,522 megawatts (MW) of electricity but can only produce about 4,000 MW. This is abysmal and clearly insufficient for national development. Delving further into the statistics in these studies [4-5], about 90 million Nigerians have limited to no access to grid-supplied electricity and this has brought about a need to develop off-grid systems to salvage the situation.

Leading the charge in the deployment of mini-grid systems are private investors while the role of government is minimal. A significant number of off-grid systems obtain part of their electricity from renewable sources and are sited in different parts of the country. This paper therefore seeks to identify the extent of deployment of the national grid, the number, capacity and locations of isolated/off-grid mini-grids and the number and types of government and privately owned grid-connected independent power producers (IPP). Also to be determined is the population served by grid-based and off-grid systems and the methods by which such off-grid systems can be smartly integrated into the national grid to better serve the electrical energy needs of the country.

Aspects of the work here reported have been researched by several authors including [3, 6-9]. However, their work has been limited to the determination of the extent of the conventional grid, determination of electrical energy consumption per capita, deployment of renewable energy resources and the need for an improved mix for electrical energy generation. Specifically, Olaniyan [3] estimates the electrical energy consumption per capita and shows that there is a huge variation in residential electrical energy consumption between different geopolitical zones of the country. The paper however did not consider energy generated from renewable sources. An overview of the extent of the conventional grid is reported by Oyedepo et al [6], in addition to identifying gaps between supply and demand of electricity. The paper also emphasizes the importance of a decentralized renewable energy deployment within the country. [7] and [8] identify the crises within the Nigerian energy sector and analyze how to effectively and strategically deploy renewable energy sources to achieve an energy mix that can better power the country. Finally, [9] uses software-based techniques to investigate how solar, wind, hydro and diesel sources can be optimally deployed to power mini-grids in different parts of the country.

The rest of the paper is organized as follows: Section 2 reviews literature on the electrical power grid system in Nigeria and examines the generation, transmission and distribution sectors of the grid while some currently deployed mini-grid systems are reviewed. Section 3 deals with the methods employed for determining the gaps in grid-suppled electricity and presents the results of the ensuing analysis. Section 4 discusses the technologies that can be utilized to integrate present and future mini-grids into the conventional grid and schematically proposes how such technologies can be deployed. Section 5 summarizes the ideas presented and concludes the paper.

2. Literature Review: The Electrical Power Grid System in Nigeria

The establishment of an electrical power grid in Nigeria can be traced back to 1886 when the first two power generating plants were commissioned by the British in Lagos [10]. However, the commencement of commercial grid operations had to wait until 1929 when the Nigerian Electricity Supply Company was incorporated [11]. Other significant dates in the development of the Nigerian power grid are 1951 and 1962, being the respective years when the Electricity Corporation of Nigeria (ECN) and the Niger Dams Authority (NDA) were established. Afterwards came the National Electric Power Authority (NEPA), which from 1972 to 2005 was a quasi-governmental parastatal responsible for all aspects of electricity generation and utilization. NEPA was establish via a merger of ECN and NDA and its persistent failure to meet the demands of Nigerians in terms of electrical power generation, transmission and distribution eventually led to its demise and the subsequent formation of the Power Holding Company of Nigeria (PHCN) in 2005.

The Electric Power Sector Reform (EPSR) Act of 2005 created the Nigerian Electricity Regulatory Commission (NERC) to oversee the electrical power industry which at the time comprised 3 gas-fired power generating companies at Egbin, Sapele and Ughelli; 3 hydro-based plants at Jebba, Kainji and Shiroro; 11 electricity distribution companies and one transmission company [10]. As at 2015, the power generation industry had grown to 25 operational grid-connected generating plants [12]. Furthermore, NERC and the Rural Electrification Agency (REA) were formed to drive progress in the industry and maintain a high level of transparency in the electrical power supply market. They have also been tasked with diversifying power generation sources by ensuring that sizeable contributions are derived from nuclear and renewable energy plants [13-14].

Some other significant milestones in the development of the electrical energy industry in Nigeria include year 2010, which witnessed the unveiling of the road map for power sector reform. This brought about the privatization of most of the generation companies and all of the 11 distribution companies. However, the transmission company was still left for 100% ownership by the Federal Government of Nigeria and was hence given the name, Transmission Company of Nigeria (TCN). Shortly after the privatization exercise was the signing of the nuclear energy Memorandum of Understanding (MoUs) in 2012, which was quickly followed by that of the coal power partnerships in 2013. Additionally, there have been some recent attempts at formulating new renewable energy development programmes, improvement of investment opportunities in stand-alone and integrated mini-grids, and a sustained drive for the completion of government and privately-owned power plants under the National Integrated Power Project (NIPP) [14].

2.1. Current State of the Conventional Electrical Power Grid in Nigeria

As at August 2015, the Nigerian electrical power grid had 25 grid-connected power plants in operation with a total installed capacity 12,522 MW from 22 gas-fired and 3 hydro-electric plants [12]. However, due to factors such as gas availability constraints, water management issues, inadequate power transmission infrastructure and vandalism of power distribution equipment, the average available and operational capacity were respectively reduced to 7,141 MW and 3,879 MW [12]. Several studies including [15] indicate that the quoted electrical power figures have remained fairly unchanged up until June, 2018 and due to reported slow progress in the industry, would still be accurate past August, 2019.

According to the industry regulator (NERC), the Nigeria Electric Supply Industry (NESI) is made up of eight major participants. These include NERC, the Federal Ministry of Power, 25 grid-connected electricity generation companies (GENCOs), TCN, 11 electricity distribution companies (DISCOs), the Nigerian Bulk Electricity Trading Company, the Gas Aggregator Company of Nigeria, and the Nigerian Electricity Management Service Agency (NEMSA). Since one of the objectives of this paper is to determine the extent of operation of the conventional national grid and various mini-grids, and to identify the percentage of populace with access to electricity, the following subsections will briefly examine the activities of three participants of NESI whose activities directly impact the stated objectives. These activities include electrical power generation, transmission and distribution.

2.1.1. Electrical Power Generation

Nigeria's power baseline report of 2015 [12], indicates that all the operational power generating plants in the country are operated sub-optimally, with up to 7 out of the 25-grid connected plants producing less than 10% of installed capacity. Using data sourced from these studies [10, 12], Table 1 provides a breakdown of the output of grid-connected GENCOs. It is indicative to note that all the thermal power plants are sited in 11 southern and middle-belt States while the 3 hydro-electric plants are sited in Kwara and Niger States.

Table 1. *Nigeria's Electrical Power Generation.*

S/N	GENCO	TYPE	INSTALLED CAPACITY[1] (MW)	AVERAGE OPERATIONAL CAPACITY[1] (MW)
1	Egbin	Thermal	1,320	539
2	Afam VI	Thermal	685	455
3	Okpai	Thermal	900	375
4	Delta	Thermal	480	374
5	Jebba	Hydro	570	262
6	Olorunsogo Gas	Thermal	335	189
7	Ihovbor	Thermal	434	182
8	Geregu NIPP	Thermal	450	179
9	Kainji	Hydro	720	173
10	Olorunsogo NIPP	Thermal	760	171
11	Omotosho NIPP	Thermal	500	169
12	Omotosho Gas	Thermal	335	163
13	Shiroro	Hydro	600	153
14	Geregu Gas	Thermal	414	131
15	Sapele NIPP	Thermal	450	111
16	Ibom	Thermal	190	76
17	Sapele	Thermal	504	69
18	Alaoji NIPP	Thermal	720	67
19	Odukpani NIPP	Thermal	561	64
20	Afam IV-V	Thermal	724	2
21	ASCO	Thermal	294	0
22	Omoku	Thermal	110	0
23	Trans Amadi	Thermal	150	0
24	AES Gas	Thermal	180	0
25	Rivers IPP	Thermal	136	0

[1]Average of daily production from 1st January to 15th August, 2015

2.1.2. Electrical Power Transmission

The transmission network in Nigeria consists of about 15,022km of 132kV and 330kV transmission lines and over 159 substations. The theoretical capacity of the transmission network stands at 7,500MW and this does not cover every part of the country [11]. According to these studies [11-12], the present transmission wheeling capacity of the transmission network is 5,300MW, which presently is higher than the average operational generation capacity of 3,879MW. The transmission infrastructure is basically radial with very long transmission lines that lack built-in redundancies and this inevitably leads to high transmission losses across the network as well as infrastructural and operational challenges [11-12]. Figure 1 shows the extent of the power grid in Nigeria.

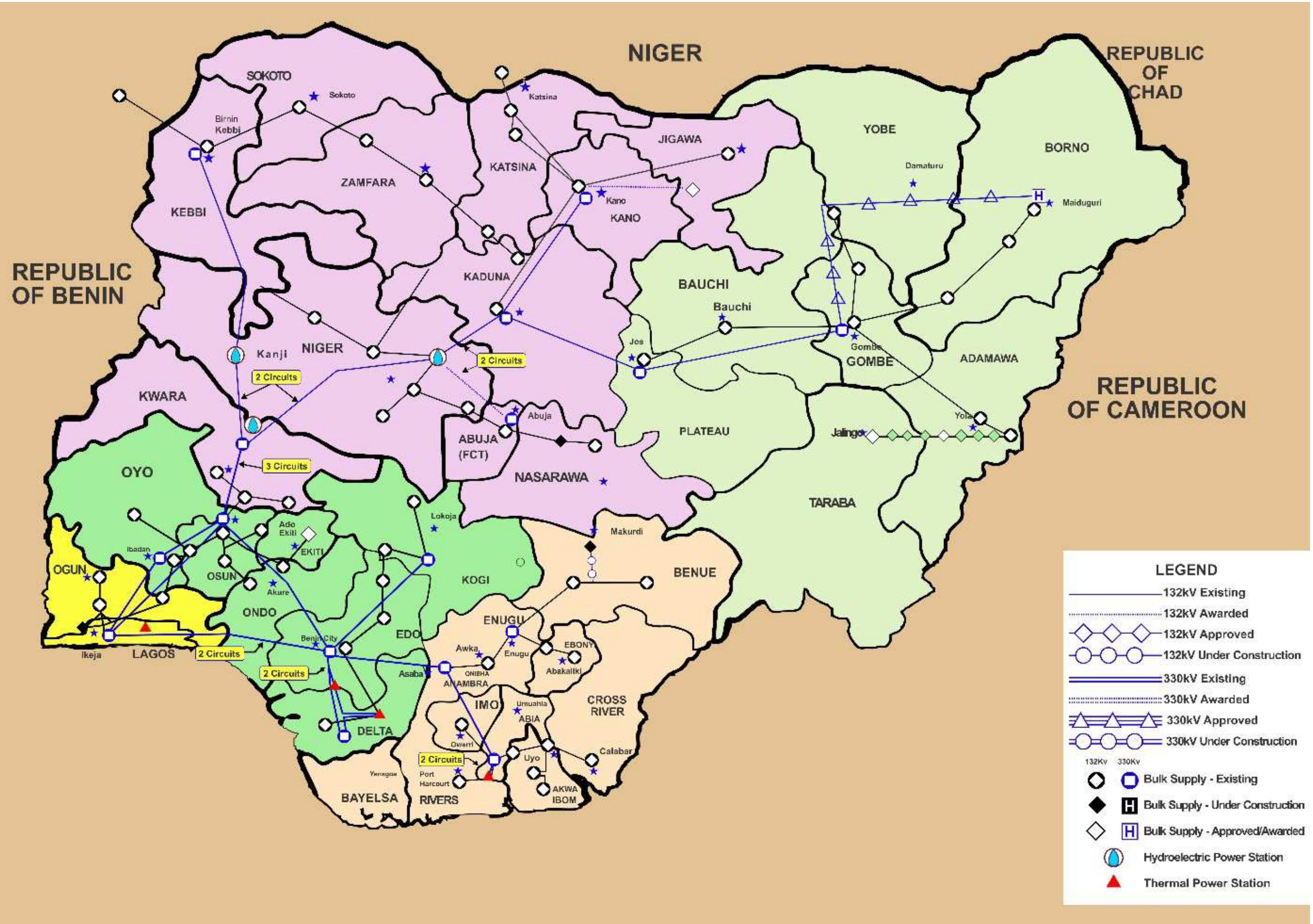

__Figure 1.__ Extent of the Electric Power Transmission Grid in Nigeria (Image sourced from [10]).

2.1.3. Electrical Power Distribution

Distribution of electricity is currently handled by 11 private distribution companies (DISCOs) that were unbundled from PHCN into different regional power distribution grids. Based on information in these studies [11-12], the coverage area of each of the DISCOs is shown in Figure 2 while Table 2 provides information on their respective customer numbers and percentage of allocated electrical energy. Electrical power in Nigeria is distributed at nominal line to line voltages of 33kV, 11kV and 415kV according to NERC regulations [16].

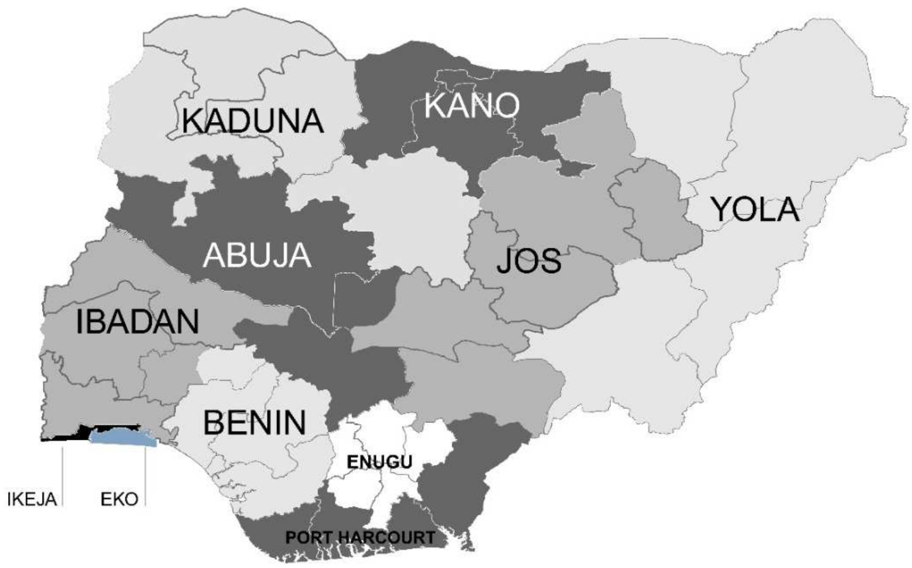

__Figure 2.__ Coverage Area of Nigeria's Power Distribution Companies.

Table 2. *Customers Served by DISCOs (Data sourced from [12]).*

S/N	DISCOs	No. of customers served ('000)	Extent of distribution network (km)	% of actual allocated energy (Jan 14-Apr 15)	Actual average value allocated (% of 3,879 MW)
1	Abuja	755	107,254	15%	581.85
2	Benin	1,187	104,702	14%	543.06
3	Eko	581	8,093	13%	504.27
4	Enugu	819	25,078	12%	465.48
5	Ibadan	1,750	24,355	11%	426.69
6	Ikeja	1,128	12,466	9%	349.11
7	Jos	4,600	12,227	8%	310.32
8	Kaduna	459	26,653	7%	271.53
9	Kano	598	21,041	5%	193.95
10	Port Harcourt	557	17,989	5%	193.95
11	Yola	345	6,505	2%	77.58

From the foregoing, it is pertinent to note that the development of Nigeria's electricity grid is faced with a myriad of challenges that has hindered its growth over the years. These challenges have drawn the interest of researchers and private investors and the next subsection provides an overview of recent advances in the development of mini-grids in order to gain an appreciation of the extent to which their deployment can help alleviate some of the inadequacies of conventional grid-supplied electrical power.

2.2. Mini-Grid Deployments in Nigeria

According to NERC [17], mini-grids are stand-alone power generation systems of up to 1 MW capacity that provide electricity to multiple consumers, households and businesses, through a distribution network. Mini-grids are different from embedded generation, which are basically independent power plants connected to a centralized grid system for the purposes of distributing electricity. Mini-grids are smaller in capacity compared to embedded generation or independent power plants, and are developed with an intention for them to operate independently of the local distribution licensee. Rural areas are a primary target of mini-grid deployment and have been reported in these studies [15, 18-21] to be a more cost effective and reliable means of electrification than extending the main (conventional) grid.

Over the last decade, there has been significant improvement in the deployment of mini grids by private investors in Nigeria [19]. For example, an assessment by GIZ [18] suggests that over 26 million Nigerians can be effectively provided with electricity using isolated mini-grid systems. Such systems numbering between 8,000 and 10,000 are capable of providing up to 4.4 GWh per year [17-18]. NERC, in conjunction with the Rural Electrification Agency (REA) has put in place policy frameworks to develop and regulate the mini-grid sector of the Nigerian electricity market.

The primary source of power for mini-grids in Nigeria has steadily evolved from fossil fuels (diesel-fired engines) to renewable sources. Presently, most of Nigeria's mini-grids use renewable sources, with solar PV as the dominant source. These are used in combination with mainly lead-acid batteries for the storage of excess energy. Table 3 gives a list of notable privately owned mini-grid projects in Nigeria. Most of the projects are sited in 10 States within the country and together, they serve about 2,000 households and over 250 commercial enterprises [19]. The combined system capacity of the deployed mini-grids is about 514kW and this supplies electricity to more than 10,000 individuals. All the systems here listed are rated under the 100kW threshold where NERC regulations [17] permit their operation after satisfying a simple registration process [15, 19].

Table 3. *Some Privately Owned Mini-Grids in Operation in Nigeria.*

S/N	Location (State, Town)	Type	Capacity (kW)	People Served
1	Rivers, Egbeke – Phase I	Solar PV	6	480
2	Rivers, Egbeke – Phase II	Solar PV	9	720
3	Rivers, Egbeke – Phase III	Solar PV	9	720
4	Gombe, Kolwa	Solar PV	34	1,600
5	Niger, Bisanti	Solar PV	34	1,600
6	Kaduna, Dodan Karji	Solar PV	16	443
7	Delta, Oghriagbene	Solar PV	16	N/A
8	Rivers, Ihuama	Solar PV	16	636
9	Osun, Idi-ta/Onibambu	Solar PV	24	1,180
10	Edo, Obayantor	Solar PV	38	1,180
11	FCT, Rije	Biogas	20	500
12	Niger, Tunga Jika	Solar PV	100	1652[1]
13	Sokoto, Kurdula	Solar PV Hybrid	90	N/A
14	Ogun, Gbamu Gbamu	Solar PV Hybrid	85	1722[1]
15	Gololow, Gamawa, Bauchi State	Solar PV Hybrid	10	N/A
16	Bayan Fada, Ningi, Bauchi State	Solar PV Hybrid	7.5	N/A

[1]Based on an average of 200 households per village and 5.9 individuals per household in rural areas following the population estimation methodology of the National Bureau of Statistics [23].

3. Determination of Gaps in Grid Supplied Electricity

This section examines the extent of coverage of the grid and hence determines the contributions that mini-grid systems can make towards alleviating the perennial shortage of electric power in Nigeria. Therefore, using the published numbers of customers per DISCO [12], the number of persons served is estimated using Equation (1)

$$a = 0.481xy + 0.519xz = x(0.481y + 0.519z) \quad (1)$$

The variables in equation (1) are defined as follows: a represents the number persons served per DisCo, x represents the number of customers per DISCO, y represents the number of persons per rural household, z represents the number of persons per urban household while the coefficients 0.481 and 0.591 respectively represent the ratio of population for rural and urban settlements as derived from a study [23].

To arrive the number of persons served based on the number of customers per DISCO, Equation (1) assumes that each customer is a household. Therefore, using the National Bureau of Statistics data [24] on number of persons per rural and urban household, y and z are respectively given the values of 5.9 and 4.9. Hence, the data in the sixth column of Table 4 (persons served) is generated.

Table 4. *Comparison of Access to Grid Supplied Electricity by DISCOs.*

S/N	DISCOs	Area served (km^2)	Population in served area	Customers served ('000)	Persons served	Customers served as % of population	Persons served as % of population
1	Abuja	140,628	16,117,258	755	4,062,655	4.7%	25.2%
2	Benin	57,353	17,841,450	1,187	6,387,247	6.7%	35.8%
3	Eko	1,788	6,275,299	581	3,126,361	9.3%	49.8%
4	Enugu	29,387	21,955,414	819	4,407,039	3.7%	20.0%
5	Ibadan	91,511	20,957,062	1,750	9,416,750	8.4%	44.9%
6	Ikeja	1,788	6,275,299	1,128	6,069,768	18.0%	96.7%
7	Jos	132,859	19,736,533	466	2,507,546	2.4%	12.7%
8	Kaduna	148,588	22,205,933	459	2,469,879	2.1%	11.1%
9	Kano	67,477	26,736,374	598	3,217,838	2.2%	12.0%
10	Port Harcourt	49,024	18,930,331	557	2,997,217	2.9%	15.8%
11	Yola	194,691	16,469,590	345	1,856,445	2.1%	11.3%
	Total	915,094	193,500,543	8,645	46,518,745		

In addition to using equation (1), other assumptions underlying the data of Table 4 are as follows:

Since Eko and Ikeja DISCO jointly serve Lagos State, and due to lack of data on actual coverage area by the DISCOs, the area has been equally divided into two to arrive at $1,788km^2$ each.

Since Table 4 estimates that 46,518,745 persons are served by the grid while an estimated population of 59.3% of 190 million people [2] have access to both fossil and renewable electrical energy sources, this implies that a total of 66,151,255 people are effectively out of the grid but may presently be served by a combination of renewable and other non-specific fossil fuel-based sources such as petrol and diesel generators.

Table 5. *Grid Supplied Electricity per Capita.*

S/N	DISCOs	Population in served area	Persons served as % of population	Actual average value allocated (% of 3,879 MW)	Electrical energy consumption per capita (W)
1	Abuja	16,117,258	25.2%	581.85	143.2
2	Benin	17,841,450	35.8%	543.06	85.0
3	Eko	6,275,299	49.8%	504.27	161.2
4	Enugu	21,955,414	20.0%	465.48	105.6
5	Ibadan	20,957,062	44.9%	426.69	45.3
6	Ikeja	6,275,299	96.7%	349.11	57.5
7	Jos	19,736,533	12.7%	310.32	123.8
8	Kaduna	22,205,933	11.1%	271.53	109.9
9	Kano	26,736,374	12.0%	193.95	60.3
10	Port Harcourt	18,930,331	15.8%	193.95	64.7
11	Yola	16,469,590	11.3%	77.58	41.8
	Country Average		30.0%	356.16	90.8

Table 5 shows that out of the 59.3% of Nigerians that have access to electricity, only about 30% are served by the grid at an average per capita consumption of 90.8W. Data is unavailable for the per capita consumption of the remaining 29.3% of the population while 40.7% do not have access to electricity at all. Therefore, using the methodology of the World Bank study [25], where electrical energy per capita is calculated at the mid-year mark, the amount of electrical energy available from the grid can be calculated from

$$b = 24hrs\,\frac{365q}{2p} \quad (2)$$

In equation (2), *q* represents the instantaneously available electrical power while *p* represents average population. Inserting the appropriate figures into equation 2 gives a value of 89.4kWh, which is 55.6kWh less than the figure quoted in [25]. An explanation of this difference can be attributed to the energy consumption of 29.3% of the population plus the backup self-consumption of the 30% of those supplied by the grid. These are very low figures when compared with values from other MINT [26] group of countries being 2157 kWh, 812 kWh, and 2847 kWh for Mexico, Indonesia and Turkey respectively.

4. Results and Discussion: Technologies for Integrating Mini-Grids into the Existing Conventional Grid

As mentioned in the preceding sections, the main sources of energy for the electricity grid in Nigeria are fossil fuel-based thermal plants and hydro-electric plants. These serve only about 30% of the population at a per capita power consumption of 90.8W and 89.4kWh of electrical energy per year. Renewable energy plants and other non-renewable sources only supply power to stand-alone mini-grids and these are estimated to serve at least 29.3% of the population. Integrating renewable and non-renewable stand-alone sources into the main grid would result in a hybrid system, which in turn would require the use of smart grid technology for its management. A smart grid can therefore be described as an electricity distribution network that allows for duplex exchange of power between players that hitherto were viewed as suppliers and consumers. For bi-directional energy flow to be possible, smart grids make use of intelligent communication, monitoring and management systems. These systems include advanced metering infrastructure (AMI), flexible alternating current transmission systems (FACTS) and high voltage direct current (HVDC) transmission lines. A proposed solution at integrating conventional and mini-grids is shown in Figure 3. The following subsections discuss the adoption of the underlying technologies within the Nigerian context.

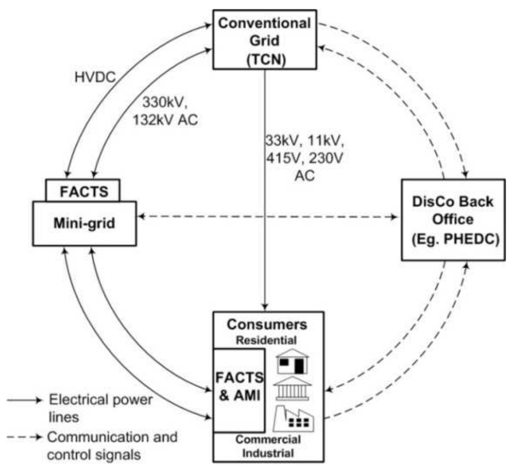

Figure 3. *Integrated smart grid showing enabling technologies.*

4.1. Advanced Metering Infrastructure

Advanced metering infrastructure (AMI) comprise smart meters, which are installed at customer premises to monitor and collect electricity consumption data, advanced communication network to transmit collected data to the utility companies and a meter data management system (MDMS) to process and store data for the purposes of billing, tamper, outage and theft detection [27, 28]. Smart meters are digital/electronic devices capable of sampling and sending data at regular intervals. They incorporate load controlling devices which enable them accept command signals to switch on or switch off specific loads. Hence they are capable of bi-directional communication and are sited at the consumer end of the integrated smart grid system shown in Figure 3.

4.2. Flexible Alternating Current Transmission System

Flexible Alternating Current Transmission Systems (FACTS) are needed for the integration of mini-grids to conventional grid because they allow for flexible, dynamic and innovative control of the power system, especially the control of quality and quantity of power in alternating current transmission lines. FACTS moderate how power flows in a particular line and promptly responds to stability problems, which is particularly useful when handling the stochastic behavior of renewable energy resources.

FACTS controllers are of different kinds, with each configured uniquely. Examples include Static Synchronous Compensator (STATCOM), Static VAR Compensator (SVC), Unified Power Flow Controller (UPFC), Convertible Series Compensator (CSC), Inter-phase Power Flow Controller (IPFC) and Static Synchronous Series Controller (SSSC) [29, 30]. As shown on the left side of Figure 3, FACTS devices such as STATCOM and UPFC should be deployed at the interface between the mini-grid and the conventional grid and between the distributed generation end (consumer end) and the evolved smart grid. This would control the voltage and offer stability, which would help mitigate the issues associated with the variable and unreliable nature of renewable energy.

4.3. High Voltage Direct Current Transmission Lines

High Voltage Direct Current (HVDC) transmission lines are needed because of their ability to transmit bulk power over long distances with minimal losses in the transmission lines. They also lend themselves to more efficient control of power flow and supply voltage stability. As shown in Figure 3, HVDC lines can be used in sending excess power from mini-grids to the conventional grid. Also, HVDC can be used as a component of FACTS.

5. Conclusion

The gaps in Nigerian electrical power sector range from generation inadequacies, limited transmission infrastructure to distribution bottlenecks. These need to be urgently attended to by the different players within the sector. This paper has given an overview of the extent to which the conventional grid and mini-grid are currently deployed within the country, identified the population served by the conventional grid and proposed a method of using the infrastructure of the smart grid technologies to integrate several isolated mini-grids for more effective delivery of electrical energy. A unique and practical approach that considers the application of technologies such as AMI, FACTS and HVDC for the integration of mini-grid into the national grid has been presented.

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