Technology Options for Increasing Electricity Access in Areas with Low Electricity Access Rate in Nigeria

(Interim Report)

by

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Abstract

This study examines the cost-effective technology option for increasing electricity access in two states with low electricity access rates in Nigeria i.e. Taraba and Yobe, from their present level of 10.9% and 18.1% respectively to 50% within a 10-year investment period. This means providing electricity access to about 267000 and 282000 households in Taraba and Yobe States respectively. We employ the Network Planner Tool – a web-based decision support program which integrates geospatial information with demographic and energy demand information, and compare three electrification options: grid-extension, mini-grid diesel-based system, and stand-alone option which uses solar PV home systems supplemented by small diesel system for productive use. The results show that grid-extension is the cost-effective option for 91% and 79% of the demand nodes in Taraba and Yobe respectively; the mini-grid option is the least-cost cost option for the remaining demand nodes; while the stand-alone option is not cost-effective in any demand node. The total cost of achieving the 50% penetration rate within the investment period in Taraba State is US$962.38million, where grid-extension accounts for 93.33% and mini-grid account for 6.67%. The total cost of achieving the 50% penetration rate within the investment period in Yobe State is US$1.03billion, where grid-extension accounts for 87.25% and mini-grid account for 12.75%. Sensitivity analysis indicates that the mini-grid becomes cost-effective for more demand nodes with lower cost of energy storage. The study sets the stage for future studies to use more accurate data from households' survey to build on.

Keywords: ***Electricity access, rural electrification, technology options, network planner, Nigeria.***

1. Introduction

The importance of modern energy services to the socio-economic development of an economy has been extensively documented in the literature. Access to modern energy services is closely related to improvements in other indices of human development such as health care, water supply, education, environmental sustainability, agricultural development, etc. (Kanagawa & Nakata, 2007, 2008; Sokona *et al*., 2012). On the contrary, inadequate supply of energy is a barrier to economic growth and adversely affects the quality of life of persons. Moreover, the impact of energy transcends national borders as energy supply can be used as a foreign policy instrument and to promote regional and international cooperation. The electricity sector is of particular importance in the energy sector because of the versatility of the end-use of electricity when compared to other forms of energy. Through time, the importance of electricity to the daily activities of people has increased and the provision of electricity and other forms of energy in an efficient and reliable manner is desirable to any society. Consequently, policy makers in a country endeavor to make adequate plans to address potential challenges and ensure short, medium, and long term energy security for the country as well as for its citizens in a sustainable manner.

Despite having an abundance of energy resources which include crude oil, natural gas, coal, hydro, and other renewable energy resources, Nigeria's electricity sector is faced with several challenges. There is a mismatch between energy resource availability and key indices of electricity sector performance. Publicly distributed electricity generation in Nigeria is dominated by hydro and gas-fired plants with an installed capacity of 1900MW and 6558MW respectively (United Nations Economic Commission for Africa, UNECA, 2011). However, by the end of 2012, the combine operational capacity of all the generating facilities was below 4600MW (Federal Government of Nigeria, 2013). As a fast-growing economy with a population of over 165 million (World Bank data) and a rising number of middle-class, the demand for electricity in Nigeria is much higher than the effective capacity to supply. Daily data on peak generation and peak demand forecast from March through October, 2014 from the website of the Presidential Task Force on Power Reforms[1] showed that peak generation fluctuate between 2500MW and 4500MW while peak demand is over 12500MW yielding a supply gap of between 8000MW and 10000MW. This results in sporadic outages in areas that are connected to the grid. Moreover, only about 56% of the population had access to electricity in 2013, with the access rate in the

[1] http://www.nigeriapowerreform.org/

urban and rural areas being 84% and 34% respectively (National Polulation Commission, NPC, 2014). There is, however, much disparity in electricity access rates across the 36 states - with Lagos State having an access rate of 99.3% and Taraba State 10.9% (Fig. 1). This disparity is mainly because of:

(i) the disparity in population density across the states - the states in the southern part are generally densely populated while those in the north-eastern part are generally sparsely populated (see Fig. 2); and
(ii) the geographic coverage of the transmission lines - the transmission lines cover most areas in the south where gas-powered thermal generating facilities are located but not the North-Eastern part of the country which does not have any generating facility (see Fig. 3).

Expectedly, the states with low electricity access rate also perform poorly in other socio-economic indices, e.g., health, literacy, child mortality, etc. (NPC, 2014)

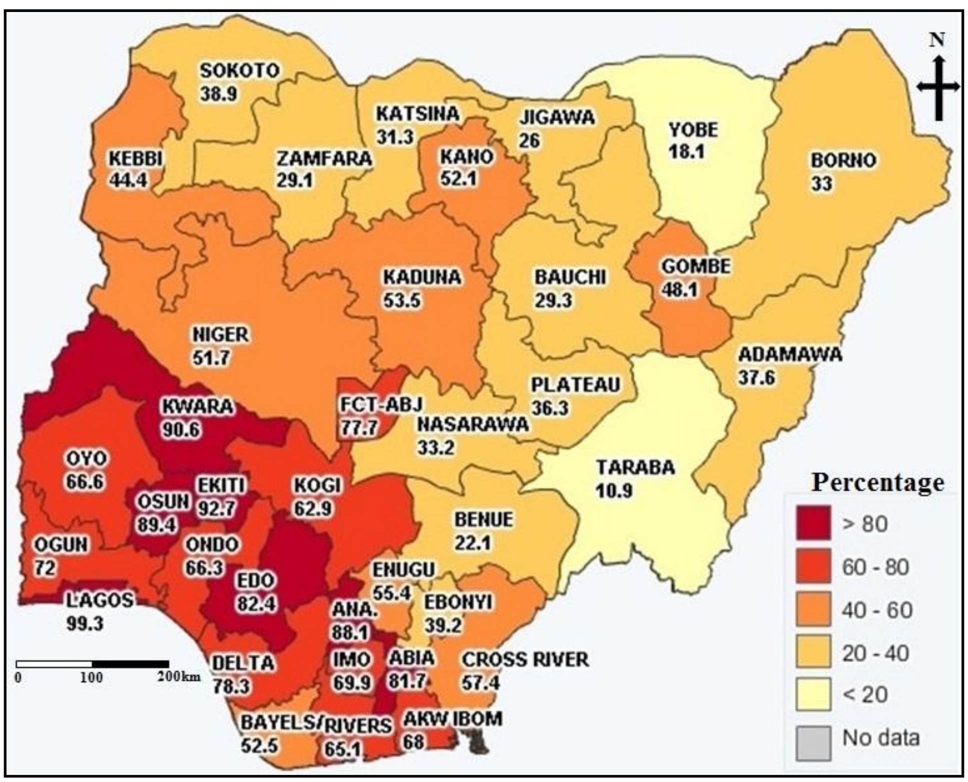


Figure 1: Percentage of households with electricity access in the different federating units (states) in Nigeria
Source of data: NPC (2014)

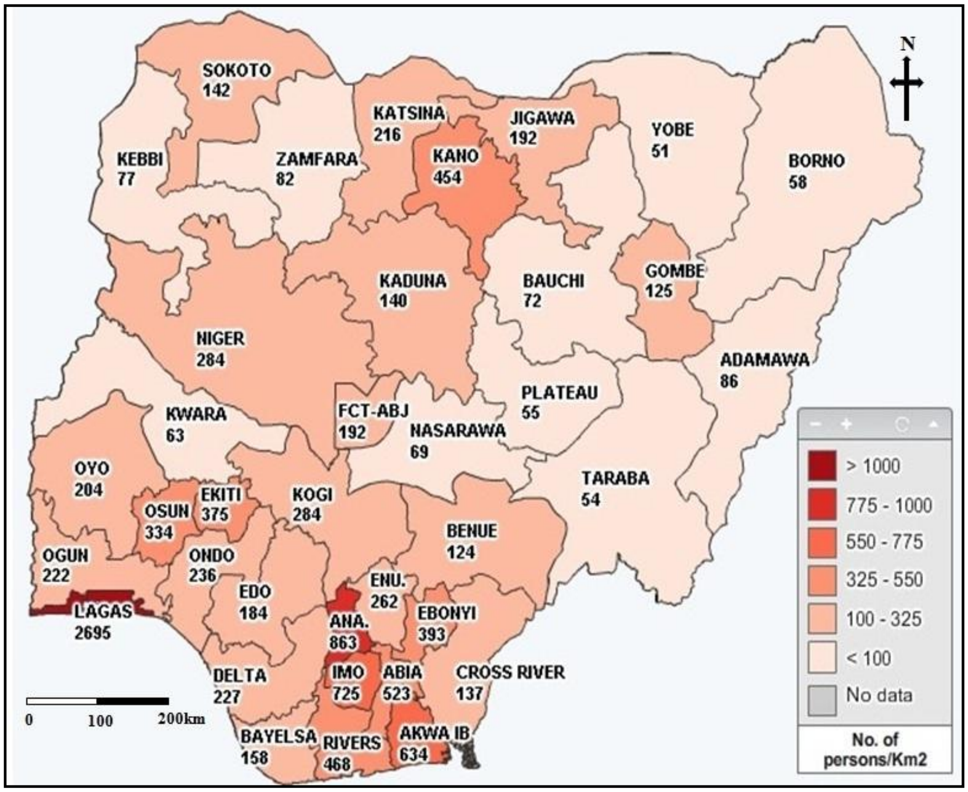


Figure 2: Population density of the different federating units
Source of data: 2006 National Population Census Report, National Population Commission, Nigeria

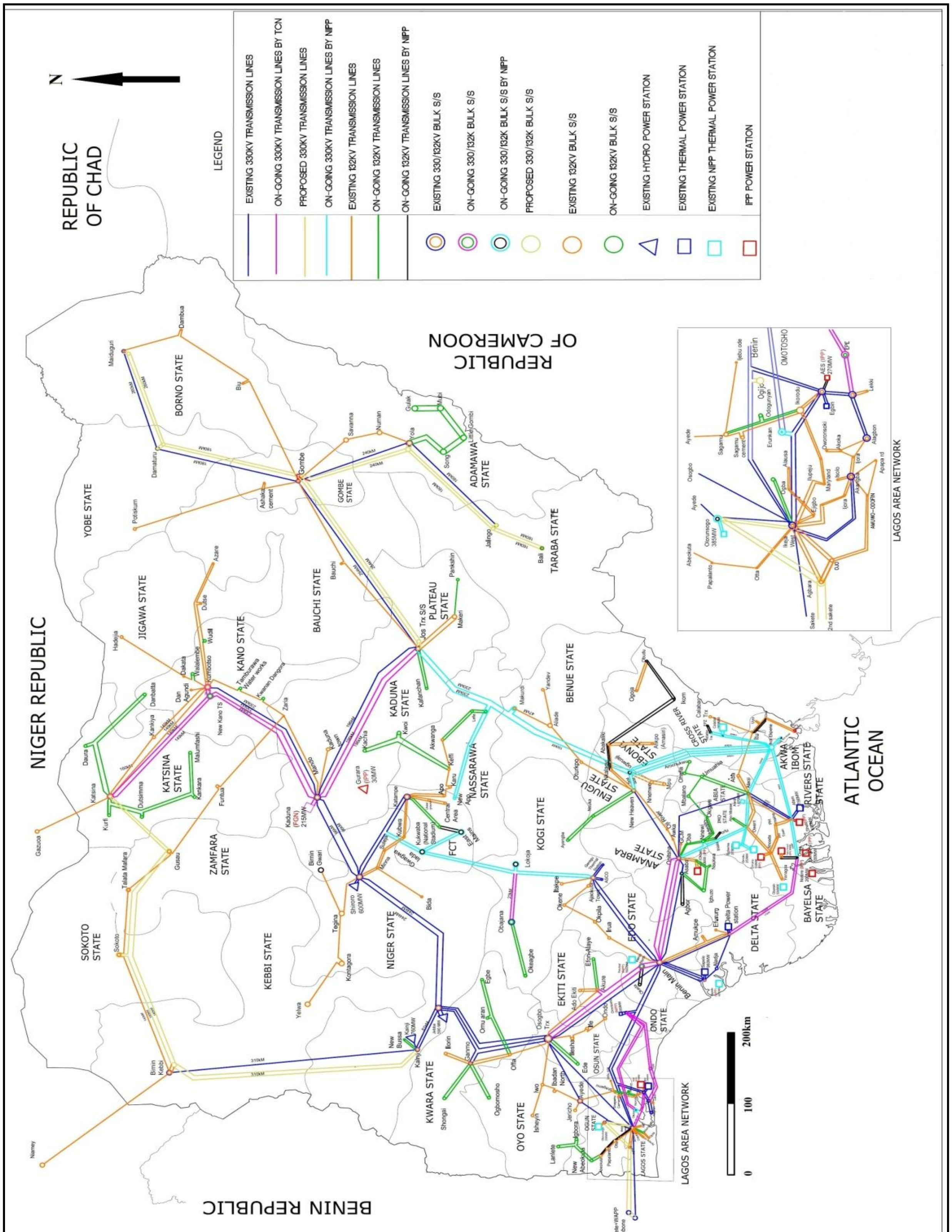


Figure 3: Map of Nigeria showing existing, ongoing, and proposed generation and transmission (HV) projects
Source: Transmission Company of Nigeria

Recognizing the importance of electricity access to its socio-economic transformation, the Nigerian government has carried out comprehensive reforms in the electricity sector. One of the objectives of the reform is to improve reliability and access to electricity across the country with a view of attaining universal electricity coverage in the shortest possible time. In Nigeria, as in many other countries in sub-Sahara Africa, the most common strategy of providing electricity access to yet-to-be-electrified communities is by grid-extension. Grid-extension requires huge financial investments in high voltage transmission lines, and medium or low voltage distribution lines. However, several studies in different parts of the world have shown that decentralized electrification, whether mini-grid or stand-alone systems, is gradually becoming an economically viable and sustainable technical option for providing electricity to areas where extending the existing grid may be too expensive, physically impossible, or lead to gross under utilization of the electricity (World Bank, 2008; Herran & Nakata, 2012; Bhattacharyya, 2012a). Irrespective of its high cost, extending the existing grid may still yield net economic returns if it serves areas that are densely populated and persons who can pay for the services to ensure optimal utilization of the electricity. Therefore, to achieve increased electricity access in Nigeria, energy planners need to adopt a multi-facet approach which involves the combination of grid-extension and off-grid electrification in a manner that minimizes cost and maximizes electricity utilization.

Several energy planning models which possess different characteristics and can be applied to address diverse energy planning objectives have been developed and used extensively in the energy sector. An overview of some of these models can be found in Cormio *et al*. (2003), Jebaraj & Iniyan (2006), Hiremath *et al*. (2007), Bhattacharyya & Timilsina (2009), Suganthi & Samuel (2012), Bhattacharyya (2012b).

Since rural areas in many developing countries are characterized by low access to electricity (International Energy Agency, IEA, 2010), some studies have approached electricity planning from the direction of increasing access to electricity at the country level, sub-national regional level, or in rural areas. The main objective of these studies is to maximize access to electricity in the study area using a least-cost combination of technology options (Sant & Dixit, 2000; Ramana & Kumar, 2009; Hiremath *et al*., 2010; Herran & Nakata, 2012). Because of the interaction of the electricity sector with several other aspects of the economy, the objective of maximizing electricity access is viewed in the context of techno-economic feasibility of technology options, and in terms of other socio-political, environmental, and governance factors (Bhattacharyya, 2012b). The techno-economic aspects considers the reliability and sustainability of the technology options, operating capacity, financial viability, cost-effectiveness, attractiveness of the option to a potential investor, and the economic benefits of the option. The governance aspect considers whether the existing institutions in the country have the capacity to implement the proposed technology options; the socio-political aspect considers the acceptability of the proposed technology option, affordability issues as well as the development outcomes of the technology option such as local income generation, women empowerment, etc.; while the environmental aspect considers the adverse environmental effects of the technology option (Bhattacharyya, 2012b).

Some studies that have focused on increasing access to electricity in areas with low access have adopted methods that choose the cost-effective option between extending the existing grid to deliver electricity and using off-grid electrification option to deliver the same amount of electricity (Sinha & Kandpal, 1991; Nouni *et al*., 2008; Parshall *et al*., 2009; Deichmann *et al*., 2011). The option of extending the grid include the capital cost of constructing transmission and/or distribution lines to load centers with different levels of load factors, the potential transmission/distribution losses, as well as the cost increasing generation capacity; while the off-grid option covers the cost of using different locally-available resources for electricity generation to meet similar load levels. With this procedure, one can obtain: the specific distance; the level of demand; and the load factor under which off-grid electrification will be cost-effective. Kaijuka (2007) used geographic information system (GIS) to visualize demographic information on location of households and institutions and used the information to project energy demand patterns and priority investment areas for rural electrification using grid or off-grid technologies in Uganda.

Parshall *et al*. (2009) incorporated geospatial information on population settlement patterns into an electricity planning model to identify the least-cost technology option for providing electricity to different demand centers in Kenya where urban and rural electrification rate was 30% and less than 10% respectively. The study also applied the Kruskal's minimum spanning tree algorithm[2] to select a set of load areas that will minimize the total cost of grid extension. The result of the study showed that under most geographic conditions, grid-extension was the cost-effective option especially in urban areas and rural areas with dense population. Sanoh *et al*. (2012) employed a similar approach in Senegal to identify areas where decentralized electrification will be cost-effective; the cost effective option between solar photovoltaic (PV)-diesel systems and diesel mini-grid off-grid options in areas were decentralized option is cost-effective; and the

[2] In Graph Theory, a spanning tree is a connected graph that connects all points on graph without any cycle. A minimum spanning tree (MST) is a spanning tree that has the smallest weight. The Kruskal's MST algorithm is an algorithm for obtaining a minimum spanning tree developed by Joseph Kruskal in 1956.

sensitivity of the options to different cost drivers. Similarly, Kemausuor *et al*. (2014) applied the Network Planner Tool (NPT), a web-based decision support for exploring cost of different electrification technology options in communities not connected to the electricity grid. The NPT is based on the methods used by Parshall *et al*. (2009).

This study intends to examine the technology options for increasing electricity access in two states with the lowest electricity access rates in Nigeria by applying an electricity planning model following similar studies in Kenya (Parshall *et al*., 2009), Senegal (Sanoh *et al*., 2012), and Ghana (Kemausuor *et al*., 2014). Studies of this nature require data at a very granular level – often from households' survey. However, such survey data that fits well into the framework of this study are not presently available. We rely on available survey data from Demographic and Health Survey and complement same with literature. We also make realistic assumptions where data are totally unavailable. Therefore this study may be viewed as a background study which sets the stage for future studies to use more accurate survey data to build on.

The study is organized as follows: after this Introduction, we will present details of our model (Section 2). In Section 3 we will present our results and we will discuss the results in Section 4. Section 5 will be the Conclusion and Policy Implications.

2. Methodology

Our objective is to obtain the cost-effective option between grid-extension and decentralized electrification for providing electricity to regions with low electricity penetration in Nigeria and we draw largely from the methodology in previous studies (Parshall *et al*. 2009; Kemausuor *et al*., 2014). In particular, we use the web-based decision support tool called Network Planner which combines data on electricity demand and cost of supply for different technology options, socio-economic variables of un-electrified communities, macroeconomic variables (interest rate, economic growth rate), and geographic information system (GIS) information to select the cost effective option for providing electricity access within a given timeframe to communities in a dataset using the simplified Kruskal's algorithm where the condition of connecting *all* points is simplified to connecting *only points for which grid extension is the cost-effective option* (see Appendix A for more elaboration). This helps decision makers to understand the least-cost option for achieving electrification targets

2.1. Focus areas and demand center

As shown in Figs. 1-3, the states in the southern part of Nigeria have higher population density (due to much smaller landmass) and electricity access rate than those in the northern part, and the transmission lines also cover most part of the south but not the north. Therefore, we assume that grid-extension will be cost-effective in the south. Our focus therefore is on states in the North where electricity access rates and population densities are relatively low. In particular, we focus on the states with electricity access rates below 20% i.e. Taraba and Yobe States. The demographic characteristics of the States are presented in Table 1. Demand centers or nodes correspond to the smallest administrative units in a country for which data on socio-economic characteristics of households which influence household energy demand and electricity access rate are available. For example, Parshall *et al*. (2009) used the sub-location level which fourth tier of administrative divisions in Kenya as demand centers. Our study uses wards[3] which may be considered as the fourth tier of administrative division in Nigeria as demand nodes.

Table 1: Characteristics of selected States

State	Electricity access rate[a]	Population (million)[b]	Landmass (sq. km)[b]	Pop density (persons per sq. km)	Number of LGAs[b]	Total number of wards[c]
Taraba	10.9	2.29	60,291.82	38.06	16	168
Yobe	18.1	2.32	46,909.76	49.49	17	178

Sources: a – NPC(2014); b – 2006 Census report; c - Independent National Electoral Commission (2013)

2.2 Modeling procedure

The modeling procedure used by the Network Planner model[4] is as follows:

(1) The user loads data on base-year population and spatial information (latitude and longitude) of the demand nodes. The user also uploads a digitized map (a shapefile) of the electricity grid of the area where the demand nodes are located. The model uses the data on the spatial location of the demand nodes to map the demand nodes in relation to the location of the existing grid on Google Earth, and then to calculates the spatial distance of the demand nodes from the nearest medium voltage line.

(2) The user sets a population threshold value based on the range of data on population of the demand nodes. The population threshold value is a value below which demand nodes are assumed to be rural.

[3] In Nigeria, there are three primary tiers of administration, namely, federal, state, and Local Government Areas (LGAs). The federal is the central government; and there are 36 states, and a federal capital territory. Each state is divided into LGAs and there are a total of 774 LGAs. Each LGA may further be divided into wards which are the lowest officially recognized administrative area. The number of wards varies from time to time (especially during elections) because some wards are merged while others are split. Presently, there are 8809 wards in the country.

[4] Details of the application may be found here: http://networkplanner.modilabs.org/

(3) Using the population threshold value and data on the population growth rate for rural and urban demand nodes respectively, the model projects the population of each demand node from the initial to the final year of the investment time horizon. With this procedure, it is possible for a demand node to begin as rural in the initial year and end as urban at the end of the investment period.

(4) Using population value of each demand node in conjunction with data on average household size, economic growth, income elasticity of electricity demand and a specified household electricity demand level, the model computes total household residential electricity demand (in kWh) and peak demand (in kW) for each demand node up to the end of the investment period.

(5) Because households in larger settlements tend to have higher electricity demand level than households in smaller settlements, the application models the variation of electricity demand across demand nodes of different sizes using three possible demand curves (linear, logistic, and linear-logistic). This is done by using user-defined demand-scaling factors which are computed from average household electricity demand for ranges of demand nodes populations, and assigning the demand scaling factors to the population ranges as multipliers such that households in demand nodes with higher population have higher electricity demand.

(6) Following a procedure similar to (5) above, two types of multipliers i.e. number of facilities and energy consumption level of facilities are also assigned to institutional and commercial demand. The aim of this is to highlight the fact the demand nodes with higher population tend to have higher number of institutions (schools, health facilities, etc.) than demand nodes with small population, and institutions in demand nodes with

higher population tend to consume more energy than institutions in demand nodes with smaller population.

(7) To examine the least-cost technology option for increasing electricity access in each demand node, the application examines three options: grid-extension, diesel-based mini-grid, and off-grid electrification using solar PV stand-alone system for home use supplemented by diesel stand-alone system for productive use. The cost of grid-extension is divided into two parts: "external cost" and "internal cost". The external cost is the cost of extending the nearest medium voltage (33 or 11kV) line and associated accessories to a 33/0.4kV or 11/0.4kV transformer station in the demand node, while the internal cost comprises the cost of the 33/0.4kV or 11/0.4kV transformer, 0.4kV distribution lines and associated accessories, and the 0.24kV lines connecting the households to the distribution lines. The maintenance cost is also added to the capital cost. The cost of the mini-grid option includes the capital, maintenance and fuel cost of the diesel-based system as well as the cost of low tension (0.4kV) distribution lines and related accessories and the cost of linking the households to the distribution lines. The cost the off-grid option is the capital cost of the solar PV system and the capital, maintenance and fuel cost of the diesel system. The costs are discounted over the specified investment period.

(8) Using the information from (3) – (7), the model compares the discounted cost of the decentralized options (mini-grid and stand-alone) and selects the option with the lower cost. Thereafter, the lower-cost decentralized option is compared with the internal cost of grid extension: if the discounted cost of the lower-cost decentralized option is lower than the internal cost of grid extension, the former is selected as the least cost option for providing electricity to the demand node because it is consistently lower than the other

two options. On the contrary, if the internal cost of grid extension is lower than the lower cost decentralized option, the model computes the difference between the two options. This difference represents the amount of budget available for use in extending the nearest medium voltage line to the demand node (i.e. the external cost). Furthermore, the model divides this value by the unit cost per meter of extending the medium voltage line to obtain a key decision metric 'MV_{max}' for each demand node. The MV_{max} which is expressed in meters indicates the maximum length of medium voltage line for which the cost of the lower-cost decentralized option will equal the cost of grid-extension for each demand node.

(9) Finally, the model uses the simplified Kruskal's MST algorithm in conjunction with information from (1) and (8), to identify the demand nodes that justify grid-extension.

2.3 Data requirement and sources

The data required for the study may be grouped into five categories: geospatial, electricity demand patterns, demographic, economic, and cost.

2.3.1 Geospatial data

Data on the geospatial location (latitude and longitude) of the demand nodes are needed alongside data on the coverage of the existing need to compute the distance of the communities from the existing grid. As noted in section 3.1, our demand nodes are electoral wards and data on their spatial location were obtained online from the website showing the location of all electoral polling booths in Nigeria[5]. In particular, the location of polling booth number 1 in each ward was used. However, the coordinates for all wards were not available; therefore, the actual number of wards covered is 157 for Taraba and 172 for Yobe. For the spatial location of the electricity grid, the digitized map for the transmission lines in Nigeria (ArcGIS shapefile) produced by the Africa Infrastructure Country Diagnostic program was used[6]. The digitized map covers existing medium voltage lines in Nigeria up to 2008.

2.3.2 Demographic variables

Demographic data used in the model are population threshold, average household size (rural & urban), annual population growth rate (rural and urban), average inter-household distance. Population data in Nigeria are disaggregated up to the LGA level but not to the ward level. We use the LGA population values from the 2006 Census Report, project them to 2013 level using annual population growth rate, and for each LGA we spread the value equally across the wards (demand nodes). The range of populations for the demand nodes in each State is 10,000 to 27,000 for Taraba, and 7500 to 29000 for Yobe. The population threshold for the demand nodes is 22000 for each state. Rural and urban population growth rates are put at 0.8% and 1.5% respectively. The average inter-household distance (which refers to the average distance between household in the demand nodes) can significantly affect the cost of low-tension distribution lines in a demand node (Zvoleff *et al*., 2009). Data for inter-household distance in the demand nodes are not available so we use assume 25m following (Kemausuor *et al*., 2014). Values for average household size (4.2 for urban and 4.9 for rural) were obtained from the 2013 Demographic and Health Survey (NPC, 2014)

[5] https://www.nigeriadecide.org/polling_unit_locator.php (accessed October 18, 2014)
[6] http://infrastructureafrica.org/documents/tools/list/arcgis-shape-files?page=7 (accessed October 18, 2014)

2.3.3 Electricity demand of load centers

The electricity demand of each load center is the sum of all household, productive, commercial, and institutional electricity demand. The low electricity access rates in the focal States indicate that electricity demand in many households and institution is non-existence and will be created when households have access to electricity. To facilitate our study, we make practical assumptions on the projected level of electricity demand in the load centers. We note that end-use of energy at the household level in areas without access to electricity is mainly for lighting and cooking. Kerosene lamps and candles are often used for lighting while cooking is done using traditional biomass and kerosene (Adkins *et al*., 2012). Access to electricity is expected to cause a gradual shift in the energy source for lighting but not necessarily for cooking. For example, Baiyegunhi & Hassan (2014) observed that with increase in income, many rural households do not switch from traditional biomass to kerosene, liquefied petroleum gas (LPG), or electricity as their main source of cooking, but rather use both traditional and cleaner energy sources. IEA (2010) also noted that rural communities with access to electricity still rely on biomass for cooking. Additional demand for home appliances like televisions will be created afterwards.

Electricity access will reduce the barriers to creation of household microenterprises or improve the productivity and profitability of existing ones (Akpan *et al*., 2013a), and many households will also own microenterprises which will create additional electricity demand in the long-run. Moreover, load centers will have institutions like schools, health centers, mosques/churches, administrative offices, etc which will also need electricity. We create our household, productive, and institutional demand profile by drawing insights from previous studies (Adeoti *et al*., 2001; Adkins *et al*., 2012; Akpan *et al*., 2013b; NPC, 2014). Our assumptions on the electricity demand of the households in the demand node with the lowest population are presented in the supplementary data sheet.

In particular, values used in the different menus of the Network Planner are as follows:

(1) Demand (peak) - Peak demand as fraction of nodal demand occurring during peak hours [rural] (0.25); Peak demand as fraction of nodal demand occurring during peak hours [urban] (0.33); Peak electrical hours of operation per year (2920 hours/year);
(2) Household demand - Household unit demand per household per year (247.52kWh/year). This value is the demand level for households in the demand nodes with the lowest population values for each State. We also assume a realistic target household penetration rate of 50% at the end of investment period. The values for the demand scaling factors are included in the supplementary datasheet.
(3) Productive demand - Productive unit demand per household per year (287.04kWh/year). Population and multiplier list values are included in the supplementary sheet.
(4) Social infrastructure demand - Commercial facility unit demand per commercial facility per year (2MWh/year); education facility unit demand per education facility per year (427.20kWh/year); health facility unit demand per health facility per year (1266.72 kWh/year); Public lighting facility unit demand per public lighting facility per year (400kWh/year). Commercial facilities exist only in urban areas and only one exists per urban area. The population and facility count, and population and multiplier list values used are included in the supplementary data sheet.

2.3.4 Economic variables

Data on economic growth, annual interest rates, and time horizon of investment are needed to compute the discounted cost of the different technological options. We assume an annual economic growth rate based on average growth rate in the past five years, i.e. 6% (World Bank data). Commercial interest (lending) rate in Nigeria is usually high: sometimes up to 28% per annum. However, because electricity access is a social program, we assume a lower interest rate similar to that for agriculture, i.e. 10%. We assume an investment time horizon of 10years as used by (Kemausuor *et al*., 2014). Income elasticity of electricity demand is also required because income level is an important determinant of electricity demand and is useful in estimating the rate of increase in electricity demand due to change in income levels. We adopt the value of 0.58 from a previous study at the macro level (Ekpo *et al*., 2011).

2.3.5 Costs

The cost component covers cost of grid extension, mini-grid, and off-grid options. The cost of grid extension was estimated using a costing schedule for a government contract for rural electrification in Nigeria. The values are provided in local currency (Nigerian Naira, ₦) and were converted to US dollars using an exchange rate of US$1 = ₦165. Values for other variables in the sheet for grid extension were estimated using diverse sources. The values used in the Network Planner for each cost item are as follows: distribution loss (15%); electricity cost per kilowatt-hour (US cents 9.34 /kWh); installation cost per connection (US$100/connection); medium voltage line cost per meter (US$13); medium voltage line lifetime (25 years); medium voltage line operations and maintenance cost per year as fraction of line cost (0.03); transformer cost per grid system kilowatt (US$1000/kW); transformer lifetime (10 years); transformer operations and maintenance cost per year as fraction of transformer cost (0.05). The cost components for the standalone option were estimated using local rates as follows: PV system per kW (US$4000/kW); cost of diesel (US$0.95); cost of the standalone diesel generating set (US$150/kW). Other cost components used are as follows: low voltage line cost per meter (US$7.68); low voltage line equipment cost per connection (US$180); diesel generator cost per diesel system kilowatt (US$120/kW); energy storage cost per kWh (US$0.20/kWh), etc. Other values are included in the supplemental datasheet.

Screenshots of some of the steps for Taraba are shown in Appendix B.

3. Result and discussion

3.1 Base case

We present the cost outlay for each technology option in order to examine the least-cost technology option. The results are presented in Table 2. We observe from Table 2 that at the end of the 10 year investment period, grid-extension will be the least-cost technology option for increasing electricity access in 91.08% of demand nodes in Taraba and 79.07% of the demand nodes in Yobe. The least-cost option for the remaining demand nodes is the mini-grid option, and the stand-alone option is not financially viable in any demand node. The performance of standalone option in the model is mainly due to the large population of the demand nodes which range from ranging from 7500 to 29000. Providing electricity to households in demand nodes with such large population using the stand-alone option implies that the advantages of economies of scale in reducing the average unit cost of generation cannot be employed.

Table 2: Cost of increasing electricity access rate from the current level to 50% at the end of the investment period using different technological options

	Taraba	**Yobe**
Number of demand nodes	157	172
number of target households (50% of total number of households)	266571	281936
Electrification technology option for demand nodes (number of demand nodes, [percentage])		
Stand-alone	0 [0%]	0 [0%]
mini-grid	14 [8.92%]	36 [20.93%]
grid-extension	143 [91.08%]	136 [79.07%]
Investment cost (initial + recurrent over the investment period)		
Total cost (million US$)		
Stand-alone	1,717.31	1,827.08
mini-grid	1,132.56	1,203.52
grid-extension	909.78	956.01
Cost per household (US$)		
Stand-alone	6,442.24	6,480.50
mini-grid	4,248.63	4,268.78
grid-extension	3,412.89	3,390.87

The role played by the size of the demand nodes in determining the least-cost technology option is also evident in the demand nodes where mini-grid is the cost-effective option: all demand nodes that have the mini-grid option as the least-cost option have relatively smaller population when compared to those compatible with grid-extension.

Increasing access to electricity in Taraba from its current rate of 10.9% to 50% within a ten-year investment period implies providing access to electricity to about 267,000 households. The total cost for achieving this using the standalone option is US$1.72billion or US$6442 per household; the cost of using the mini-grid option is US$1.13billion or US$4249 per household; while the cost of the grid-extension option is US$909.8million or US$3413 per household. Similarly, increasing access to electricity in Yobe from its current rate of 18.1% to 50% within a ten-year investment period implies providing access to electricity to about 282,000 households. The total cost for achieving this using the standalone option is US$1.83billion or US$6481 per household; the cost of using the mini-grid option is US$1.2 billion or US$4269 per household while the cost of the grid-extension option is US$956million or US$3391 per household. We can observe from the overall cost of each technology option that grid-extension is the least-cost option, followed by the mini-grid option.

Next, we examine the cost of schedule for electrifying the demand nodes in each state using the least cost technological option for each demand node. The results for the two states are presented in Table 3. The stand-alone option is excluded because it is not cost-effective in any demand node. We observe from Table 3 that over the investment period, the total cost for electrifying the 14 demand nodes in Taraba where the mini-grid option is the least-cost option is US$37.62million. This comprises of an initial cost of US$7.86million and a recurrent cost of US$29.75million. Moreover, because the mini-grid option is to be powered by diesel which will be stored at a cost of US$0.20/kWh, an additional cost of US$26.59 million is incurred. The levelized cost for the mini-grid option is US$0.31/kWh. The levelized cost is total cost of electrification using a given technological option over the investment period divided by the total amount of electricity supplied using the technological option.

Table 3: the cost of schedule for electrifying the demand nodes in each state using the least cost technological option for each demand node.

	Taraba State	**Yobe State**
Number of demand nodes	157	172
Mini-grid nodes	14	36
Mini-grid initial cost	$7,864,636	$17,673,172
Mini-grid recurring cost	$29,754,917	$60,568,516
Mini-grid total cost	$37,619,553	$78,241,688
Mini-grid cost levelized	$0.31 / kWh	$0.32 / kWh
Mini-grid energy storage cost	$26,591,073.68	$53,528,996
Grid nodes	143	136
Grid initial cost	$303,551,972	$298,121,185
Grid recurring cost	$594,620,161	$603,876,413
Grid total cost	$898,172,133	$901,997,598
Grid cost levelized	$0.22 / kWh	$0.22 / kWh
Grid length proposed	1,328,994 m	1,331,426 m

The total cost of the increasing electricity access in the 143 demand nodes where grid-extension is the least-cost option is US$898.17 million which comprises of US$303.55million initial cost and US$594.62 recurrent cost. It is important to note the recurrent cost of grid-extension incorporates the generation cost through the end-user tariff (electricity cost per kilowatt-hour) which is put at US cents 9.34 /kWh. The levelized cost for the grid extension is US$0.22/kWh which is lower than that of the mini-grid option and reinforces that fact grid-extension is generally the least cost option for most demand nodes in the state. Furthermore, increasing electricity access in demand nodes in Taraba state will involve extending the medium voltage line to cover a total of 1328.99kilometers. The proposed length of extending the grid reflects the large landmass of Taraba State which is 60,291.82km^2 and the very small population density of 38.06 persons per km^2.

Similarly, the total cost of increasing access to electricity in the 36 demand nodes in Yobe where the mini-grid option is the least-cost option is US$78.24million of which US$17.67 is the initial cost and US$60.57 is the recurrent cost; the total cost for electrifying the 136 demand nodes where grid-extension is the least-cost option is US$902million of which US$298.12 is the capital cost and US$603.88 is the recurrent cost; the levelized costs for the mini-grid and the grid-extension options are US$0.32/kWh and US$0.22/kWh respectively; and the grid-extension option will involve extending the medium voltage line for 1331km.

3.2 Sensitivity Analysis

The study uses estimates for variables that affect electrification cost and these estimates may change over time. Changes in these variables can significantly affect the result of the study.

Sensitivity analysis is carried out to examine the impact of change in some of the variables used in the analysis. In particular, the sensitivity analysis considers the following changes: 20% increase and decrease in household demand level respectively; increase and decrease in average inter-household distance from 25m to 30m and 20m respectively; reduction in cost of solar PV system for the stand-alone technology option; and increase and decrease energy storage cost per kWh for the mini-grid option from US$0.20/kWh to US$0.15/kWh and US$0.25/kWh respectively. The changes are then compared to the base case scenario. We present in Fig. 4 the result of our sensitivity analysis for change in household energy demand.

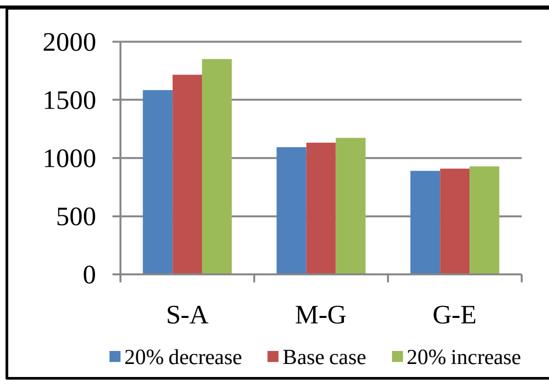
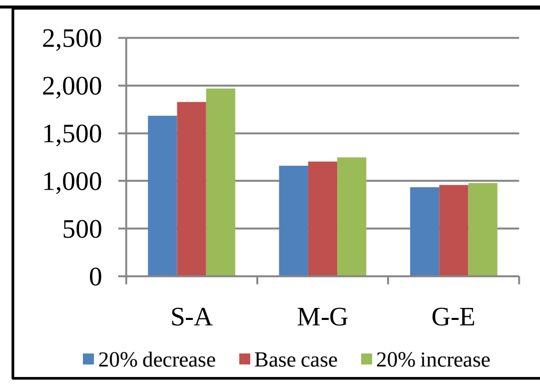
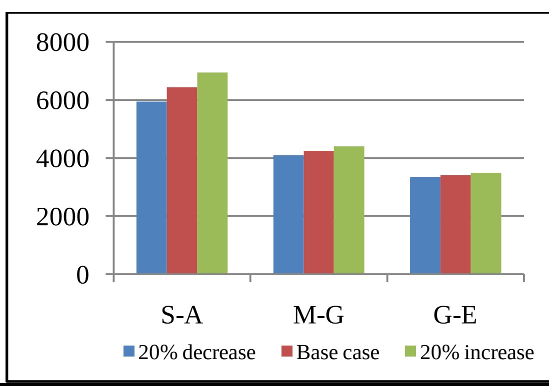
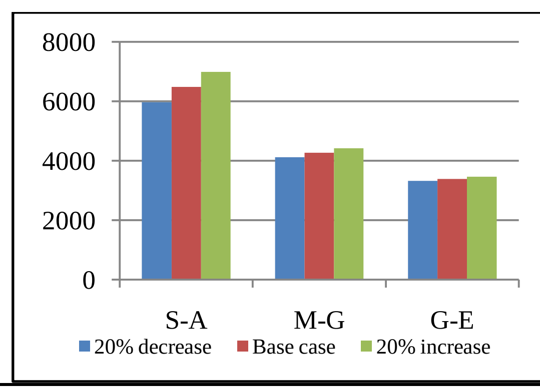
	Taraba	**Yobe**
Investment cost of the different options (million US$)		
Cost per household (US$)		
S-A: stand-alone ; M-G: mini-grid; G-E: grid-extension		

Figure 4: Sensitivity Analysis for change in household demand

A change in household demand affects the total energy demand of each demand node and in-turn the cost meeting the energy demand using each technology option explored in this study. Our results show that a 20% increase and decrease in household demand from the base case demand of 247.52kWh/year will affect the cost of the stand-alone option most while the cost of grid-extension is affected least. This trend is the same for the total cost of investment in Taraba and Yobe respectively and also for the cost of investment per household in each state. In all, the grid-extension option remains the least-cost option. Moreover, a 20% decrease in household demand will increase the number of demand nodes in Taraba compatible with the mini-grid option from 14 to 23 while the grid-extension option will be the cost effective option for the remaining 134 demand nodes. In contrast, a 20% increase in household demand will reduce number of demand nodes compatible with the mini-grid option from 14 to 2 and grid-extension will be cost-effective for the remaining 155 demand nodes. Similarly, with a 20% decrease in household demand, the number of demand nodes compatible with the mini-grid option in Yobe will increase from 36 to 46 and grid-extension will be the cost-effective option for the remaining 126 demand nodes, while a 20% increase in household demand will reduce the number of demand nodes compatible with the mini-grid option from 36 to 29 and grid-extension will be the least-cost option in the remaining demand nodes.

The result of the sensitivity analysis for changes in average inter-household distance, cost of energy storage, and cost of PV panels is presented in Table 4. For ease of presentation, we present only the cost per household and exclude the total investment cost. A change in average inter-household distance affects the cost of grid-extension and mini-grid options because they require investment in low tension distributing lines, but does not affect the cost of the stand-alone option. Nevertheless, the resulting changes in total cost of investment and cost of investment per household for the mini-grid and grid-extension options in Taraba and Yobe do not affect the number of demand nodes that are compatible with each option in each state.

A reduction in the cost of energy storage in the mini-grid option from the base-case value of US$0.20/kWh to US$0.15/kWh significantly affects the cost per household of the mini-grid-option. In Taraba, the cost per household reduces from US$4248.63 to US$3379.41; and in Yobe, it reduces from US$4268.78 to US$3397.01. This reduction affects the number of demand nodes that will be compatible with the mini-grid option in both states: in Taraba, the number of demand nodes compatible with the mini-grid option increases from 14 to 127; in Yobe, the number increases from 36 to 117. In contrast, an increase in the cost of energy storage from US$0.20/kWh to US$0.25/kWh will increase the cost per household of the mini-grid option in Taraba from US$4268.78 to US$5140.56 and will make grid-extension to be the least-cost option for all the demand nodes in the state. In Yobe, the increase in the cost of energy storage will reduce the number of demand nodes that are compatible with the mini-grid option from 36 to 11 while grid-extension will be the least-cost option in the remaining demand nodes.

A reduction in the cost of PV panels for the stand-alone option from the base case value of US$4000/kW affects only the cost of the stand-alone option. The effect of this is that it also reduces the total cost and the cost per household of the stand-alone option for both Taraba and Yobe. However, the reduction in the cost per household does not significantly affect the overall cost structure and the stand-alone option is not cost-effective for any demand node in each state.

Table 4: Sensitivity Analysis for change in average inter-household distance, cost of energy storage, and cost of PV panels

	Cost per household (US$)					
Variables/ Technology options	Taraba			Yobe		
Average inter-household distance	20m	Base case (25m)	30m	20m	Base case (25m)	30m
mini-grid	4170.55	4248.63	4326.71	4189.55	4268.78	4348.02
grid-extension	3334.81	3412.89	3490.97	3311.63	3390.87	3470.11
Cost of energy storage (mini-grid)	US$15/ kWh	Base case (US$20/ kWh)	US$25 /kWh	US$15 /kWh	Base case (US$20/kWh)	US$25/ kWh
mini-grid	3379.41	4248.63	5117.86	3397.01	4268.78	5140.56
cost of PV panels	$3500/ kW	Base case ($4000/kW)		$3500 /kW	Base case ($4000/kW)	
Stand-alone	6262.26	6442.24		6297.40	6480.50	

4. Discussion

As noted by Bhattacharyya (2012b), the objective of increasing electricity access in rural areas need to be viewed in the context of techno-economic viability of technology options, as well as other socio-political, environmental, and governance factors. From the techno-economic dimension, we observe that even though grid-extension is the least-cost technology option for increasing the level of electricity access in the two states considered, the cost layout is still relatively high due to the low population density of the states. For example, comparing the total cost per household for grid-extension in Yobe (i.e. US$3391) with the official minimum wage of US$109.1/month throughout the investment period, we observe that electricity payment will account for about 25.9% of household income at the end of the investment period[7]. The restructuring of the electricity sector in Nigeria and the privatization of the distribution segment imply that income levels of households will play a crucial role in any decision to extend the existing grid. However, household income levels in the two states (Taraba and Yobe) are among the lowest in Nigeria which is a disincentive for grid-extension as the cost of grid-extension may not be recovered. This implies that increasing electricity access in these states will require additional financial support and incentives from government at different tiers. From the institutional dimension, we observe that even though the Electric Power Sector Reform Act of 2005 established a Rural Electrification Agency (REA), the Agency is yet to be fully operational. A good start here will be to fully operationalize and finance the REA to discharge its duties.

Another problem with the option of grid-extension is the availability of adequate reserve margin in the generating segment. As noted by Bekker *et al*. (2008), one of the factors responsible for South Africa's success in providing access to electricity to over five million households between 1990 and 2007 is that the utility (Eskom) had a 55% reserve margin in its generating segment. Presently, Nigeria's situation is a sharp contrast. As noted in the Introduction, the unmet energy demand in Nigeria is between 8,000MW and 10,000MW which implies that additional generating capacity will be targeted at consumers already connected to the grid. This indicates

[7] Official minimum wage is N18000 and an exchange rate of US$1=N165 is assumed. The assumption here is that the minimum wage is not increased. Nevertheless, even though the minimum wage is doubled electricity payment will account for 12.95% of household income

that even though grid-extension is the least-cost option, the domestic situation of the country poses some challenges that will need to be resolved before the option can be implemented.

The use of diesel engine for the mini-grid option is not also without challenges in terms of the recurrent expenditure on diesel and the availability of skilled personnel in the local areas to maintain the facilities. Moreover, even though Nigeria produces crude oil, it imports a sizable portion of refined product to meet domestic needs. The diesel market in Nigeria is deregulated and the price of diesel fluctuates considerably. Therefore, in addition to the low income of households and availability of skilled personnel, the cost of fuel may be a hindrance to the smooth implementation of the mini-grid option which raises questions on the sustainability of the option. The use of a technology option that has relatively low operation and maintenance cost for the mini-grid option such as a mini-hydropower may address this problem. Indeed, small (including mini, micro, and pico-) hydropower projects holds huge potential in meeting energy needs of persons in locations where the resource abound. However, our model does not capture small hydropower because the cost characteristics of hydropower are highly site-specific and will usually require onsite techno-economic feasibility studies of the hydro-geological terrain for such projects. The hydropower potential in Taraba is sufficient for large and small hydropower plants. The state is the host state for the proposed Mambilla Power Station - a 3050MW capacity large hydropower station on the Donga River. Notwithstanding its huge potential for small hydropower plants, not much has been done by government to develop small hydro power even though the Renewable Energy Master Plan has targets for small hydropower development in the country (Energy Commission of Nigeria, ECN, 2005).

5. Conclusion and Policy Implications

The objective of this study was to use the Network Planner Tool to examine the cost-effective technology option for increasing access to electricity in two states in Nigeria with electricity access rate below 20%. Three technology options were considered: grid-extension, mini-grid using a diesel system, and stand-alone option using solar PV for home use supplemented by a small diesel system for productive uses. The study used demand nodes which are defined as the smallest administrative units in the country for which data on socio-economic characteristics of households which influence household energy demand and electricity access rate are available, and uses electoral wards as demand nodes. The result of the study shows that grid-extension is the least-cost technological option for 91% and 79% of the demand nodes in Taraba and Yobe respectively and the mini-grid option is the least cost technological option for the remaining demand nodes. The stand-alone option is not cost-effective for any demand node and the reason for this is the relatively large size of the demand nodes. Sensitivity analysis shows that the result is most sensitive to changes in the cost of energy storage for the mini-grid option. On the other hand, the result is less sensitive to capital cost of PV system and average inter-household distance. The role of small hydro power in increasing electricity has also been highlighted because of the availability of huge water resources in Taraba State which may be developed and used to meet the electricity needs of communities in the state in a mini-grid.

The result of the study would have been more detailed if the demand nodes used were at a more disaggregated level than the ward level. However, this was not possible due to unavailability of data. The non-granularity of the demand nodes has played a role in the result of the study. The challenges encountered by this study can be address by using data from detailed households' survey of communities in Nigeria without access to electricity. Such survey should be tailored to capture the various household and community-related factors that affect technology options for increasing electricity access, and will help planners in planning electricity access programs. It will also help government to set realistic electrification targets and provide accurate indicator for measuring progress. Our result has shown that mini-grid option is cost-effective in some demand nodes but the use of diesel engines may not be sustainable. We recommend that the mini-hydro schemes be accorded greater consideration as a potential option for providing electricity access in some of the communities where hydropower resources abound. The Rural Electrification Agency should develop policies which involve government at all tiers to stimulate self-help projects by training local populace on developing pico- and micro-hydropower from the hydropower resources available in Taraba, and to a lesser extent in Yobe. This may yield significant net economic returns given the benefits of such projects in terms of local ownership, development of local skills, and the environment. Furthermore, the scope of the study may be extended to cover all un-electrified communities in Nigeria.

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Appendix A: Elaboration on the use of the Kruskal's Minimum Spanning Tree

In Graph Theory, a spanning tree is a connected graph that connects all points on the graph without any cycle. A minimum spanning tree (MST) is a spanning tree that has the smallest weight. The Kruskal's MST algorithm is an algorithm for obtaining a minimum spanning tree developed by Joseph Kruskal in 1956. The procedure for obtaining the Kruskal MST states that in a set S containing n points, let W_{ij} denote the weight of any arc connecting i and j, where i, j $\in S$.

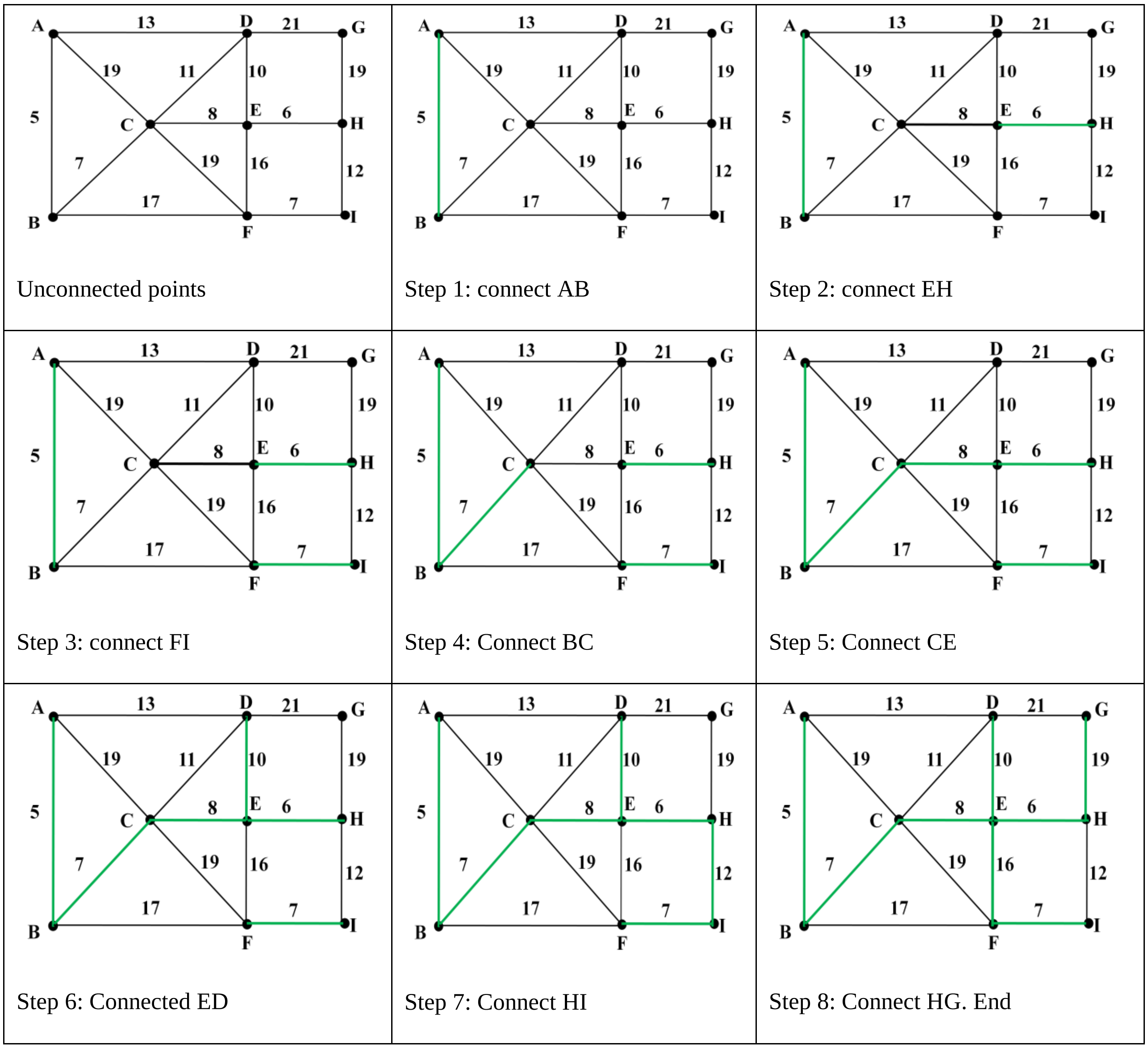
i. Select the arc with the least weight

ii. From the remaining arcs, select the arc with the least weight that does not form a cycle. If more than one then choose any.

iii. Repeat step 2 until all points are connected without forming a cycle.

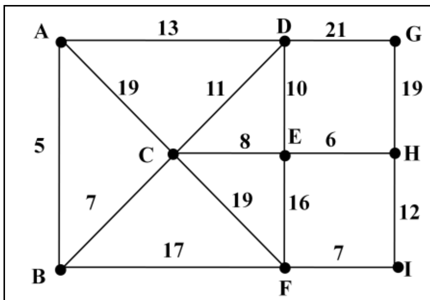
We illustrate the classical Kruskal's MST in Schematic 1.

Schematic 1: Illustration of the standard Kruskal's MST procedure

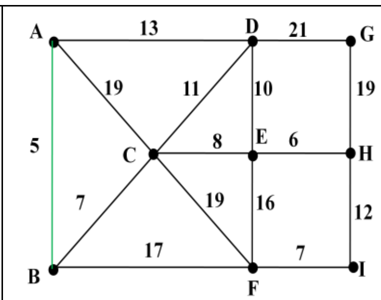


In this study, the points are the electricity demand nodes and the characteristics of the demand node are determined by the socio-economic characteristics and energy demand of households, and population of the demand node. The weight of each arc connecting the points is the determined by two factors: (i) the distance of each demand node from an existing grid which in-turn determines the capital cost of grid extension. This is directly proportional to the weight of the arc; (ii) the characteristics of the demand nodes which determine whether grid-electricity will be grossly underutilized due to low demand (load factor). This is inversely proportional to the weight of the arc. In the simplified Kruskal's algorithm used in Network Planner Tool, the ordering of the connections will differ because a new connection must be initiated from an existing connection. This implies that the spanning tree is not an absolute minimum, but a minimum given the condition that new connections are made from existing ones. The second command in the procedure stated above now becomes "From the remaining arcs, select the arc with the least weight that *is already connected* and does not form a cycle. If more than one then choose any." We illustrate this in Schematic 2.

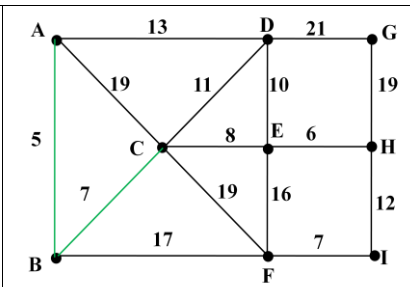
Schematic 2: Spanning tree for electrification



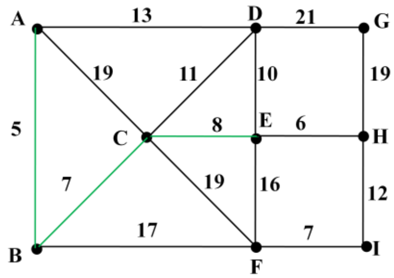
Point A represents the end of the existing MV line



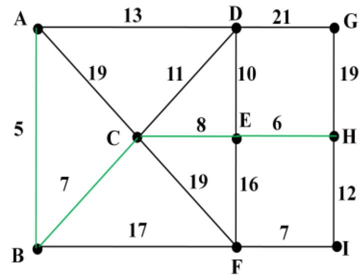
Step 1: connect AB



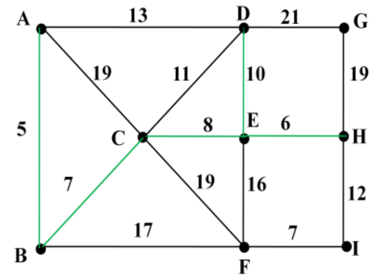
Step 2: connect BC



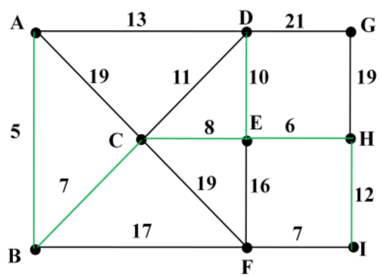
Step 3: connect CE



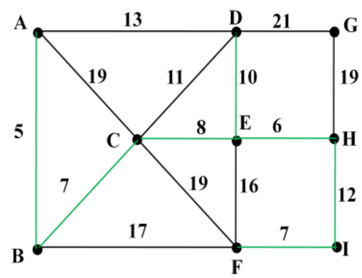
Step 4: Connect BC



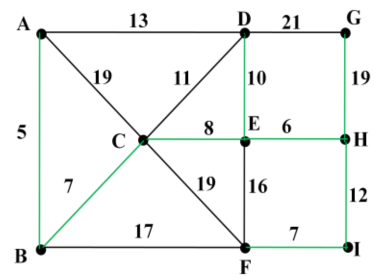
Step 5: Connect CE



Step 6: Connected EH



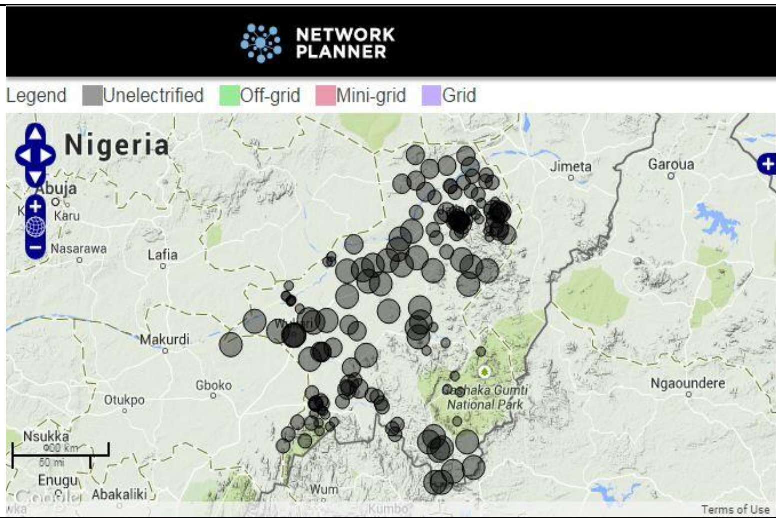
Step 7: Connect HI



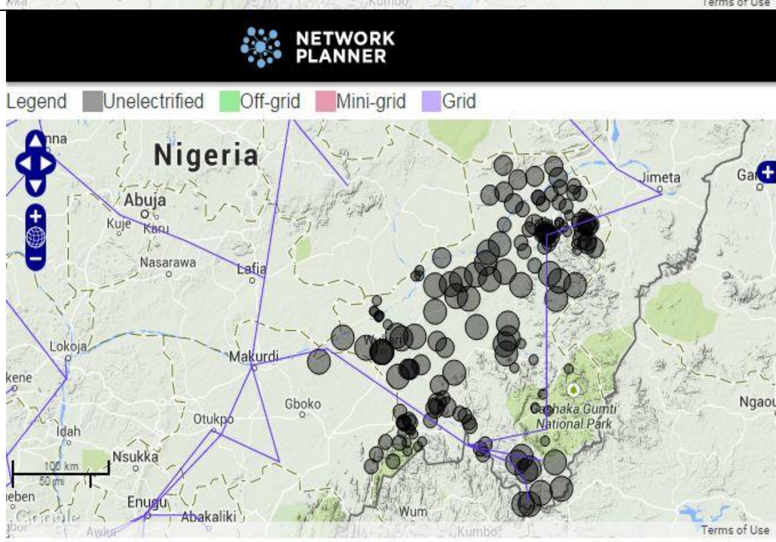
Step 8: Connect HG. End

Moreover, the condition of connecting *all* points is simplified to connecting *only points for which grid extension is the cost-effective option*. As an example, in Schematic 2, at step 8 the option of connecting point G to the existing grid are DG and HG with corresponding weights of 21 and 19 respectively which may be viewed as the cost of grid extension. If the total cost of providing electricity access to point G using off-grid option (mini-grid or solar home systems) is lower than the weights for DG and HG each, then an off-grid option is cost-effective and may be adopted.

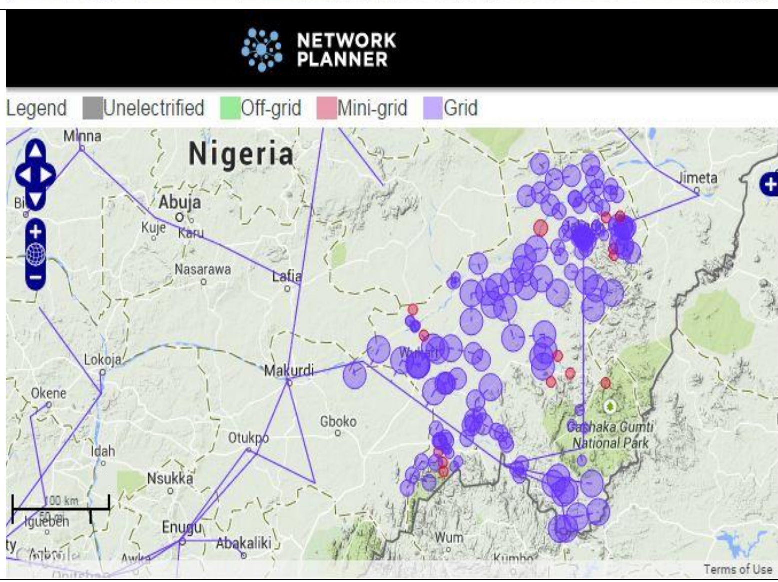
Appendix B: Screenshots of the Network Planner



Base-year population and spatial information (latitude and longitude) of the demand nodes. The size of the bubbles is proportional to the population size of a demand node.



Adding a GIS shapefile of the coverage of the medium voltage lines



Base case results showing demand nodes that are compatible with each technology option

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