INVITED PAPER

Least-Cost Electrification Modeling and Planning—A Case Study for Five Nigerian Federal States

This article presents a modeling process to derive a least-cost electrification plan for five states in Nigeria, combining energy system simulations with geospatial information system tools.

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ABSTRACT | Nigeria is the African country with the highest total number of people without access to electricity, at least 90 million. To provide sustainable and affordable energy to these people is an enormous challenge. Advanced modeling and planning are essential tools to enhance the quality of investment decisions. Planning has to address the latest electrification options [grid extension, hybrid minigrids, and solar home systems (SHS)] in a technically and economically sound way for different implementation phases. We have developed a modeling process to derive a least-cost electrification plan for five federal states in Nigeria combining energy system simulations with geospatial information system tools. Investments of approximately $1600 million for medium-voltage (MV) and low-voltage distribution infrastructure, minigrids, and small-scale systems are required to achieve a 100% electrification rate. The simulated electricity system of the five states is characterized by an overall load of about 1804 MW. The electrification options comprise different electrification measures. About 1772 MW are supplied by central power generation through the central grid via 11 579-km new grid lines. The decentralized supply sources include only a few renewable energy (RE) minigrids with a total of 3-MW load will remain isolated, while all others will be interconnected to the central grid. The decentralized supply is defined by 225-MW photovoltaic (PV), 504-MWh battery, and 198-MW diesel-based isolated and interconnected minigrids as well as by 29-MW SHS capacities.

KEYWORDS | Energy access; energy system modeling; geospatial planning.

I. INTRODUCTION

The global community acknowledges two major challenges in sustainable electricity supply: the transition toward renewable energy (RE) and the provision of energy access. Both are underlined in the Sustainable Development Goal 7 (SDG7) [51]. Ensuring access to affordable, reliable, sustainable, and modern energy for all is also interlinked with other SDGs, such as SDG13–Climate Action, SDG6–Clean Water and Sanitation, SDG8–Decent Work and Economic Growth, and SDG4–Quality Education and, therefore, results in myriad benefits to society, including improved living standards [3], [6], [34].

Globally, it is estimated that 1.1 billion people still lack access to electricity, of which 630 million are living in sub-Saharan Africa [17]. Nigeria is the African country with the highest total number of people without access to electricity and a high population growth at the same time, leaving at least 90 million people without access. Providing them access to electricity comes with many challenges [53]: among them are technical and economic barriers to connect remote and rural areas by grid extension. Decentralized supply options get increasingly competitive compared

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to grid extension but also add complexity to electrification planning. These can be standalone diesel generators or systems based on RE or a combination thereof. Detailed spatial and energy system analyses are necessary to derive least-cost electrification plans for certain regions, villages, or settlements [2]. Such planning, when informed by the latest electrification options (grid extension, minigrids, and small-scale systems), has improved the prospects for decision-makers to establish a basis for robust technical and economic outcomes [45].

A broad range of electrification planning tools exists, each with particular strengths and weaknesses. These tools have been developed in order to address specific questions with regards to a different level of detail, e.g., on a single project level or tools deriving electrification options for larger regions, covering different technological solutions. A gap analysis of four existing tools—HOMER Energy [16], [27], Network Planner [43], GeoSim [19], and OnSSET [32], [48]—presents an overview of the respective limitations of different tools and allowed us to define tool requirements for spatial least-cost electrification modeling. The main limitations identified are the lack of a holistic phase-wise electrification approach, covering detailed energy system simulation-based minigrid modeling and geospatial information system (GIS)-based grid extension modeling. Our tool development aimed at addressing these limitations in order to allow for regional phase-wise electrification electricity planning for decision-making that results in least-cost outcomes for sustainable access over the long term. Here, we develop an approach to conduct such modeling and planning to derive a least-cost electrification plan for five federal states in Nigeria combining energy system simulations with GIS tools. Least-cost electrification plans are developed and guided by the following questions.

1) Where do people without access to electricity live?
2) What is the electricity demand of these people?
3) What are the least-cost supply options for delivering this demand?
4) What is the optimized phase-wise electrification plan to implement these options?

To answer these four questions, different energy system and GIS tools have been applied for five federal states in Nigeria (Cross River, Niger, Plateau, Ogun, and Sokoto) and have been identified as applicable for least-cost electrification planning in challenging environments. The selected states cover diverse geographical areas with varied socioeconomic characteristics. Prototyping the tool along this distinct group of states allows an extended application of the developed tools to other states in Nigeria or other countries [36].

After providing background information on Nigeria, we present a critical review of electrification planning and modeling tools and elaborate on the most important requirements. This is followed by the detailed description of the developed approach of RLI's electrification planning

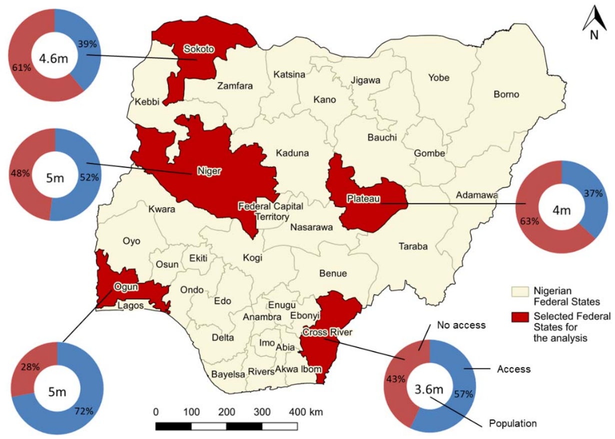

Fig. 1. ***Map of Nigeria with the states selected for the analysis displayed in red (based on [10]). Pie charts show the total population in the center and the share of people with access (blue) and without access (red) to electricity.***

tool. The application of the tool for the five federal states in Nigeria and the results are shown in Section IV. Results are discussed, and limitations are described in the following section, and this paper is summarized in the final conclusion.

Nigeria is the most populous country in West Africa, located between the Gulf of Guinea in the South and the Sahara Desert in the North. Of its 180 million inhabitants, nearly 50% have no access to a sustainable electricity supply, despite Nigeria being the second largest economy on the African continent and rich in natural resources, including fossil and RE resources.

The Nigerian power system relies largely on natural gas-fired power plants mostly located in the South of Nigeria as well as hydroelectric power plants located in central Nigeria [12], [52]. The RE share (predominantly hydro) of installed capacity is approximately 16%. According to the Nigerian Electricity Regulatory Commission (NERC), due to inadequate generation availability and delayed maintenance of facilities, real on-grid supply for Nigeria amounts to 4 GW on average and is thus at two-thirds of the available capacity (6 GW), which, in turn, is well below-installed capacity (12 GW). At present, the average daily power generation is lower than the peak forecast for the currently existing infrastructure, and consequently, decentralized electricity generation with diesel generators is prevalent across Nigeria [41].

For this study, we analyzed five selected federal states located across Nigeria: Cross River, Niger, Ogun, Plateau, and Sokoto (see Fig. 1). These federal states are selected to cover a wide range of different characteristics in terms of settlement structures, natural resource availability, current level of access to electricity, and installed energy infrastructure. Key statistics of the five federal states highlight that all these states are faced with severe electrification challenges to be overcome and ultimately supply more than 20 million people living in these five states.

Table 1 Evaluation of Electrification Planning Tools.

Criteria/Tool	HOMER [27][39]	Network Planner [43][23][4]	GeoSim [7, 20]	OpeN Source Spatial Electrification Tool (OnSSET) [32] [33]
Geospatial planning	-	++	++	+
Load modelling	++	-	+	+
Energy system analysis	++	o	+	+
Implementation phases	o	-	-	-

II. ELECTRIFICATION PLANNING AND MODELING—CRITICAL REVIEW OF TOOLS

A. Importance of Electrification Planning Tools

Given the immense challenge of improving access to electricity in many rural areas of the developing world, the application of different electrification planning tools allows for evidence-based decision-making and to shed light on technical details and options of the electrification challenge. Three aspects necessitate detailed modeling: 1) various location-specific aspects need to be considered (e.g., different settlement patterns and densities and varying demand for electricity, local resource availability, and existing infrastructure) [31]; 2) data scarcity—in many cases, detailed data and information required for an in-depth assessment are lacking, especially in countries with the largest need of improvement in electrification [46], [47]; and 3) different technical solutions [44] are available such that a one-fits-all approach is unsuitable in terms of economics and applicability. To account for these three aspects, a combination of tools is required, which combines input data creation from widely available data sets (e.g., spatial global population data sets for village cluster development) and allows geospatial planning by using GIS analyses, detailed load projections, and energy system modeling.

B. Review of Tools

We evaluated four different tools according to the requirements described above [10], [11]. The results of this evaluation are shown in Table 1.

In order to compare the tools, different criteria of geospatial planning are assessed for each tool. HOMER builds its energy system analysis on local resource availability but can only consider one location and no geospatial assessment of grid extension is possible as well as modeling of a spatial electrification across a region with different technologies. The Network planner, GeoSim, and OnSSET implement a spatial comparison of different electrification options for a given region. Within both GeoSim and the Network planner framework, only direct point-to-point connections are assumed. OnSSET geospatial planning is only based on local averages and no official administrative planning structures such as villages are considered in this raster pixel approach.

In terms of load modeling, HOMER provides the most sophisticated options creating detailed load profiles, while within the Network planner, loads are considered as peak values only. GeoSim includes detailed projections based on different user classes and surveys, and for OnSSET, a detailed load needs to be specified by the user.

The energy system modeling is implemented on different levels of detail in each of the tools: HOMER provides the most detailed minigrid design calculation with hourly simulations of different power generation components ranging from solar and wind to diesel gensets and battery systems. The Network planner considers only diesel minigrids, while GeoSim allows more variety, as well as OnSSET.

The phase-wise implementation of electrification options is not considered in the spatial tools Network planner, GeoSim, and OnSSET, while at least load growth can be considered in HOMER, but no stepwise capacity expansion.

A gap identification shows that the geospatial phase-wise modeling is limited for all available tools: HOMER only assumes specific locations for minigrids, while the other three tools simplify grid extension by considering straight connecting lines between points ("as the crow flies") only. The applicability of the discussed tools is limited to cases with very good data availability. None of the tools has a standardized interface to openly available global data sets for load demand modeling. In terms of energy system analysis, some of the tools only calculate diesel-based minigrids instead of more complex hybrid systems. Finally, the tools are not able to implement a stepwise approach that divides the electrification process in discrete steps, which are more easily implementable and, therefore, reflect a more realistic electrification pathway on the ground.

III. FOUR-STEP APPROACH TO ELECTRIFICATION PLANNING FOR PHASED IMPLEMENTATION

Based on the gap analysis, we developed our own approach that comprises of four steps combining state-of-the-art GIS and energy system models with on-site data acquisition and validation. The approach is cluster-based, meaning that consumer clusters (e.g., settlements, villages, and towns), which must be identified beforehand, are used to derive the electrification plan. The plan is developed in the following four consecutive steps, based on the defined requirements.

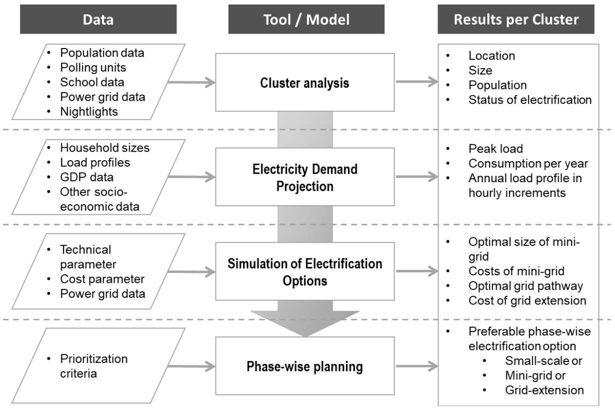

Fig. 2. ***Stepwise electrification planning approach.***

1) Identification of population cluster and their status of electrification based on population data, grid infrastructure, and night light satellite imagery.
2) Projection of electricity demand of each cluster is conducted by applying an algorithm, which creates annual load profiles in hourly increments based on socioeconomic data.
3) Simulation of different supply options and least-cost optimization for each cluster: grid extension costs are based on a least-cost pathway algorithm showing the most cost-effective grid connection of each cluster based on topography and spatial relations. Hybrid minigrid costs are calculated based on the optimized configuration of photovoltaic (PV)-battery–diesel systems supplying the load at the lowest levelized cost of electricity (LCOE). Small-scale systems are suggested for clusters with low electricity demand.
4) Phase-wise implementation planning is conducted based on the simulation results and prioritization criteria. For each cluster, the technically and economically optimal supply option is assigned within three electrification phases allowing grid extension, off-grid hybrid minigrids, interconnected minigrids, and small-scale systems. In this section, the steps are explained as shown in Fig. 2.

A. Cluster Analysis—Where Do People Without Access to Electricity Live?

A prerequisite for any geospatial electrification plan is the knowledge on the location (detailed geospatial coordinates) of settlements and the existing electric infrastructure. Such data were not available for the studied Nigerian states in the required spatial resolution at the time of the creation of the electrification plan. Our cluster identification tool helps to overcome these data gaps and set the baseline for further planning. This tool identifies certain areas—presented as clusters—which could be supplied by one distribution grid network. These clusters represent small settlements comprising of a few people up to large cities.

The main input parameters for the identification of clusters are spatially resolved population data [30], [46], polling units [18], and schools [42]. Processing this data through the cluster identification tool allows for the calculation of location, size, and number of people for each cluster within the respective state. The first step is to find the location and size of each cluster. For this, each densely populated area, polling unit, and school are buffered with a 500-m buffer zone. Overlapping zones are merged into one larger cluster as shown in the process flowchart in Fig. 2. The cluster populations are determined in four steps, which are validated by local census and field data.

1) Global raster population data are reclassified in areas with high and low population densities (>7 ppl/pixel).
2) Population is summed up per cluster.
3) The number of pupils per cluster is chosen to readjust the global population figures.
4) The overall population figures per state as published by the Nigerian National Bureau of Statistics are taken to scale the total number of people for all clusters.
5) 10% of the people in clusters with less than 20 000 inhabitants are selected to be assigned as dispersed people who live in nonpermanent residences or very small scattered settlements.

Finally, the number of people per cluster, the location of each cluster, and the number of dispersed people are known. Next, the status of electrification of each cluster needs to be determined. For this electrification plan, the connection of the cluster to the central power supply system—grid—is the decisive factor. As a proxy for grid connection, the appearance of night light emissions derived from satellite imagery is taken. If night lights are detected within a certain cluster or it is located along the line between the two electrified clusters, it is selected as grid connected. All remaining clusters are defined as clusters without access to electric infrastructure, which form the baseline for further planning. The first step of the electrification planning process is summarized in the following flowchart.

B. Demand Projection—What Is the Electricity Demand of Those People?

To conduct a least-cost comparison of electrification options for each rural village, referred to as cluster, it is necessary to assess the energy demand and load profile. To derive such profiles for each cluster in a reasonable timeframe, an automated computing method is required. Therefore, a demand projection algorithm is developed based on GIS tools and statistical algorithms (cf. Fig. 3). It is based on the previously derived cluster data, specific load profiles from measurements and literature [1], [40], and other socioeconomic data as well as experts' recommendations [35], [37].

The key part of the electricity demand projection tool is to derive an individual daily load profile for each cluster,

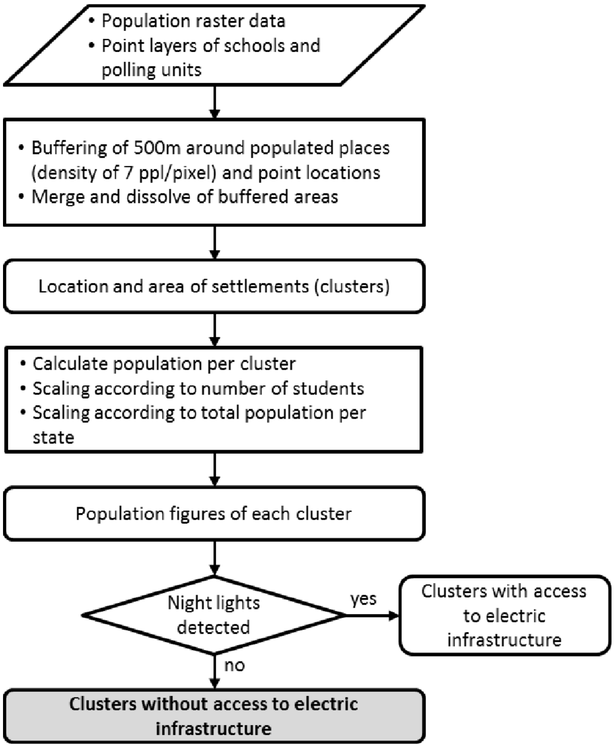

Fig. 3. ***Flowchart of cluster identification.***

which is then extrapolated to calculate an annual profile. Ten different consumer types with individual daily profiles and consumption patterns are identified and applied to each cluster according to the respective population and economic activity [50]. Categories and specific daily consumption values are listed in Table 2. The demand projection model includes individual hourly load profiles for the presented categories. Fig. 4 shows the applied load profiles in percentwise consumption per hour.

Household profiles distinguished in low, medium, and high consumption are presented [see Fig. 4(a)]. The household consumption groups depend on the wealth of a single household and differ in their load factors. Thus, we take the expected income per household as a decisive factor for household consumption profiles as it has been observed before [29], [38]. On the other hand, low consumption households mainly use light bulbs in the evening; medium and high consumption households possess more appliances (i.e., television, radio, and fridge), which increase the baseload during daytime. Commercial and productive users generally require electricity for powering appliances during working hours [see Fig. 4(b)]. Productive loads (i.e., welder, carpenter, and ice factory) peak during noon and afternoon. Commercial loads instead (i.e., grocery, barber shop, and appliance store) peak in the evening hours, reflecting higher loads for lighting as these places serve customers after work. Water pumps are mainly applied in the morning and evening hours, and agricultural appliances (e.g., mills) are operated during the day [see Fig. 4(c)]. Health facilities with high consumption reflect rural hospitals with basic medical infrastructure (e.g., fridges and sterilizers), characterized by a high baseload and low load factor. Contrasted by that, rural health stations (health facilities with low consumption) are comprised of a small amount of equipment, such as solely fridges and light appliances. Therefore, demand peaks in the evening hours. School demand can encompass a few electric appliances including ventilators, audio devices, and computers for which power is consumed during school lessons [see Fig. 4(d)]. Finally, the number of specific

Table 2 Electricity Consumer Categories for Demand Projection

Category	Daily consumption	Quantification of consumer per category
Households low consumption	0.74 kWh/day	Household number derived by population divided by average household size per state.
Households middle consumption	2.35 kWh/day	
Households high consumption	5.38 kWh/day	The share of each household category is based on the average GDP/capita in the clusters. Higher GDP/capita increases the share of households with high consumption.
Commercial use	3 kWh/day	Commercial consumption is scaled according to quantity of households and GDP/capita per cluster.
Productive use	12 kWh/day	Productive consumption is scaled according to quantity of households and GDP/capita per cluster.
Agricultural appliances	5 kWh/day	Agricultural appliances are scaled according to quantity of households.
Water pumps	1 kWh/day	Values derived from data set per cluster
Health post (low consumption)	15 kWh/day	
Health station (high consumption)	150 kWh/day	
Schools	3 kWh/day	

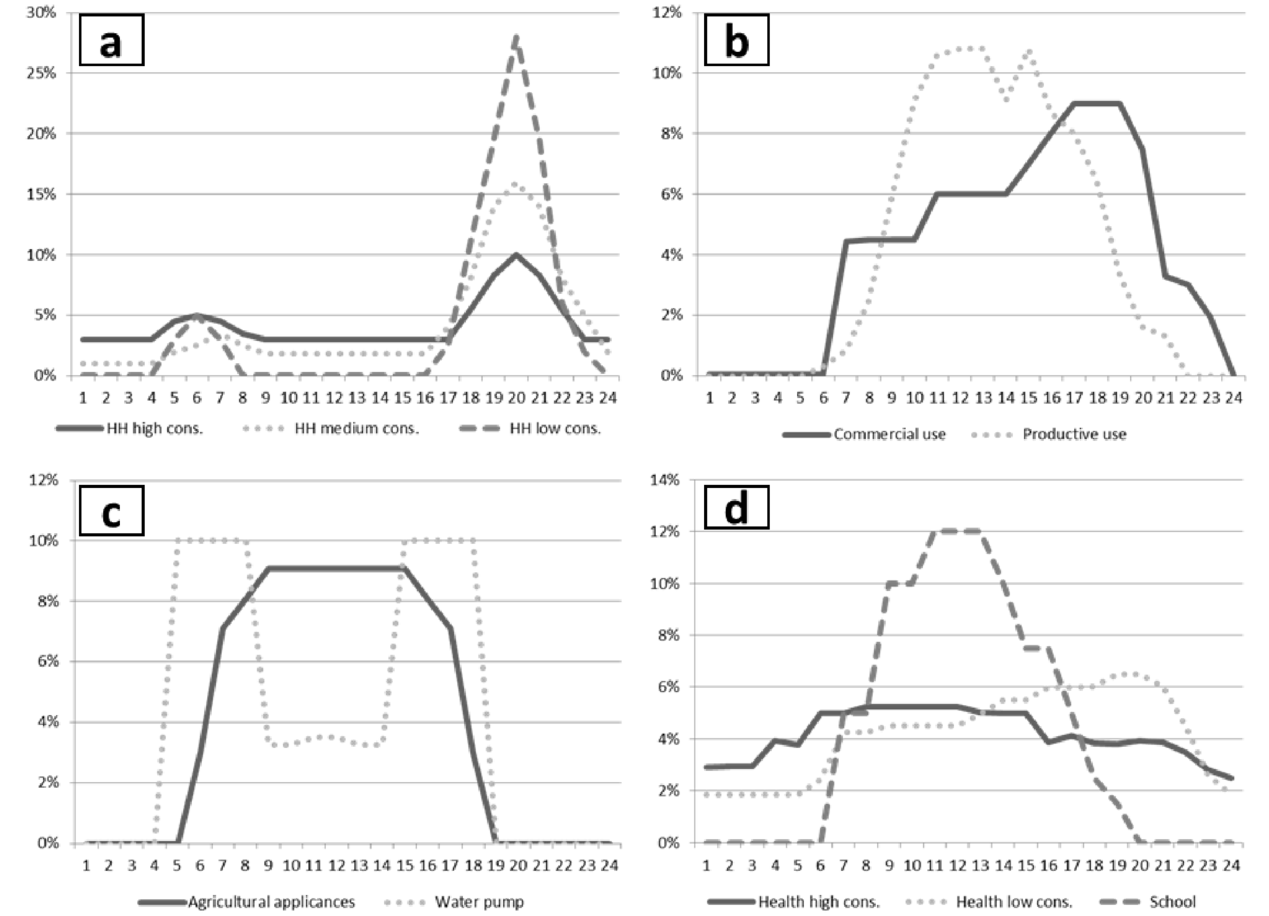

Fig. 4. ***Daily load profiles in percentwise consumption per hour applied for different categories. (a) Household load profiles for high, medium, and low consumption types. (b) Commercial and productive use load profiles. (c) Agricultural load profiles for agricultural applications (e.g., milling) and water pumping. (d) Social load profiles for large health stations (high consumption).***

consumers per cluster multiplied with the defined typical energy demand results in an energy demand specific per consumer category. This energy demand is then distributed through the identified consumer load profiles to comprise daily load profiles per cluster. These profiles are replicated to cover one entire year. In addition, the demand is scaled in certain periods of the year to reflect for higher demands for harvesting activities according to the geographical location of the cluster. Finally, a random variability is applied to cover unexpected events as well as daily and hourly variations in consumption patterns. The randomized annual profile is then scaled to the original annual consumption value to derive the final demand profile. This process is illustrated in Fig. 5.

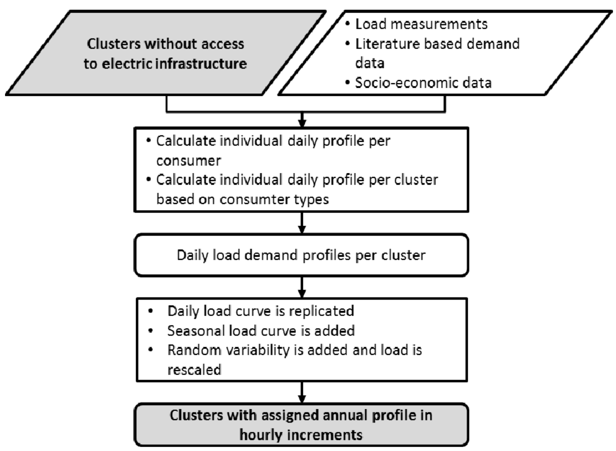

Fig. 5. ***Approach applied for projecting rural energy demands.***

C. Energy System Modeling—What Are the Least-Cost Supply Options for Delivering This Demand?

As potential supply options for the identified demand, we distinguish three solutions in the tool: solar home systems (SHS), minigrids, and grid extension. Each option is calculated individually to understand the needed capacities and respective cost figures. For minigrids and grid extension, the LCOE is calculated for each cluster individually as follows:

$$\mathrm{LCOE} = \frac{\mathrm{IC} * \mathrm{CRF}\,(\mathrm{WACC}, N) + \mathrm{Opex} + \mathrm{Costs}_{\mathrm{fuel}} * \mathrm{Fuel}}{E_{\mathrm{consumed}}}. \tag{1}$$

In (1), LCOE stands for levelized cost of electricity. Furthermore, IC stands for initial costs, CRF stands for capital recovery factor, WACC stands for weighted average cost of capital, N stands for project lifetime, Opex stands for operational expenditures per year, $\text{Costs}_{\text{fuel}}$ stands for cost of diesel per liter, Fuel stands for consumed diesel per year, and E_{consumed} stands for consumed electricity per year. The CRF is calculated as follows:

$$\text{CRF}\,(\text{WACC}, N) = \frac{\text{WACC} * (1+\text{WACC})^N}{(1+\text{WACC})^N - 1}. \qquad (2)$$

In (2), CRF per technology is calculated according to WACC and project lifetime (N).

1) SHS: SHS is small-scale systems, which combines PV and battery storage to individually supply households or other customers. The most common type is the solar lantern (∼5 W) or SHS, with capacities between 11 and 250 W, possibly combined with a battery directly supplying basic needs, such as lighting, cooling, mobile phone charging, or TV. Buying an SHS—with integrated lighting and appliances, and its “plug-and-play” nature—more closely resembles the purchase of consumer electronic products than buying a product separately and having the energy provided via the grid. SHS is already state of the art. In the second half of 2017, more than 250 000 SHS (11+ W) were sold globally [15]. SHS can be purchased on pay-as-you-go schemes and provide modern energy services for lighting, mobile phone charging, and other small appliances that are higher quality than existing solutions (e.g., kerosene lanterns). Costs related to the setup of small-scale systems include costs for PV, possibly battery storage and, in the case of nanogrids, connection costs. According to a recent report by International Renewable Energy Agency, typical costs for sub-1-kW SHS systems, which represent the vast majority of SHS sold in Africa, ranging from \$4 to \$16 per Watt [22].

In our electrification planning tool, SHS is modeled in a very simplified way. Clusters below a certain peak demand threshold (50 kW) are selected for SHS supply as it is assumed that the introduction of any distribution grid, for minigrids or grid extension, may be economically unviable for those.

2) Minigrids: A minigrid is a vertically integrated electricity supply system with its own power generation capacity, supplying electricity to more than one customer connected via a distribution grid. The generation capacities can be composed of combinations of RE and fossil power sources, such as PV, hydro, biomass, wind, and diesel complemented with battery storage systems [49]. Minigrids can operate in isolation from the central grid (isolated minigrid), typically serving loads from 50 to 1000 kW in rural areas. Minigrids, which can be connected to the central grid, are known as interconnected minigrids.

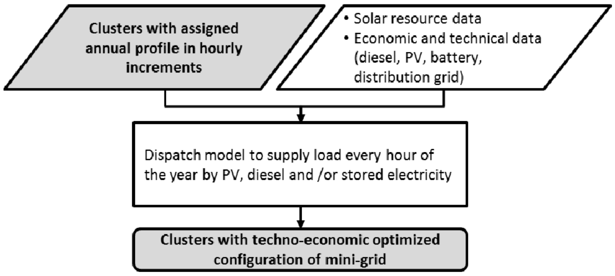

Fig. 6. ***Flowchart of minigrid modeling.***

In our planning tool, hybrid minigrids—comprised of solar PV, diesel gensets, and battery storage systems—are considered. In addition, the distribution grid for the cluster must connect every customer considered in the load projection analysis. To simulate such minigrid supply, an energy system simulation model is applied.

The minigrid simulation model assumes the combination of one diesel-based engine plant, one PV plant, and one battery storage system. It simulates one reference year in hourly increments to determine the most economical combination. A high level of security of supply acts as a boundary condition: the system must be able to match the latent load in every hour of the year. Fig. 6 shows the process of minigrid modeling.

The minigrid model works as follows. Solar resource data in hourly temporal resolution are processed to generate a PV generation profile. This is multiplied with different PV sizes and combined with various battery sizes to supply the derived load profile. Diesel gensets serve as back-up power for times with insufficient solar power supply. A hierarchical dispatch strategy maximizes the RE-share by prioritizing direct consumption of PV power or battery discharge over diesel power generation. The optimization algorithm changes the sizes of the PV and battery components until the most cost-efficient solution is found to supply the load. This model has been validated and applied for several other studies (see [8] and [9]). Technical and economic input parameters can be individually set for each technology. These parameters were discussed and validated during a technical stakeholder workshop in Nigeria and are presented in the following paragraph.

Regarding the solar PV plant, a ground-mounted system including inverters with approximately 16% total efficiency is modeled. For battery storage, a typical lithium-ion battery is assumed to have a full-cycle efficiency of 94%, approximately 5000 full-load cycles, and a maximum depth of discharge of 80%. The c-rate—ratio between power [kW] and capacity [kWh]—is chosen as 0.5. The modeled diesel gensets have efficiencies between 30% and 35% and are sized by the simulation tool to be able to cover the peak load. The distribution grid required is scaled based on the number of customers per cluster. In addition to the technical parameters, the following economic parameters are considered in the developed minigrid simulation tool as outlined in Table 3.

Table 3 Cost Assumptions for Minigrid Model Based on [14], [21], [24]

Category	Costs
Power generation (investment costs of PV and generators, including fuel costs)	PV: 1,250 USD/kW (OPEX: 25 USD/kW/a) Diesel generator: 820 USD/kW (OPEX: 0.05 USD/kWh$_{el}$) Diesel fuel: ~0.68 USD/liter
Energy storage (investment costs of battery system)	Capacity: 250 USD / kWh (OPEX: 7 USD/kWh/a) Power: 500 USD / kW
Connection distribution grid	400 USD / customer
Project development costs	20,000 USD / project
WACC	16%
Project lifetime	20 years

D. Grid Extension

The third electrification option considered in this electrification approach is the extension of the central grid, entailing extending the central grid via transmission and distribution lines toward additional customers. Grid extension allows a broader coverage of areas with access to the central grid, which is mostly supplied by central large-scale power plants.

To model potential grid extension pathways toward unelectrified clusters and their related costs, a sophisticated grid extension algorithm was developed to reflect realistic extension scenarios (cf. Fig. 7). Theoretically, one could simply connect a cluster via the shortest way to the grid "as the crow flies" and combine these connections via a minimum spanning tree (MST) approach. However, in practice, a detailed grid extension path model is required to account for topography and spatial characteristics that affect grid extension construction. For this electrification plan, a comprehensive grid extension model based on GIS was developed and applied. It serves not only to identify new grid extensions but also to overcome data gaps in the existing grid coverage. The model, input parameters, and results of the modeling of the existing grid were discussed and validated during stakeholder workshops. The underlying principles are explained in the following figure.

Five different data sets are used to create an economic decision raster data set to identify the optimum grid pathway [13]. The first and most important data set contains the location of the existing grid and its course. This is required to define the location from where the grid can be extended. In the model, these locations are weighted with zero cost, allowing the algorithm to use the complete existing grid as a starting point for grid extension with no added costs. The second data set contains the road network. Medium-voltage (MV) lines are mainly constructed in close proximity to roads due to easier accessibility of land for construction maintenance purposes. The relative cost of areas covered by roads is decreased by 75%. The third data set provides information on the location of protected areas (such as National Parks) and increases the relative cost by 50% to reduce landscape fragmentation and damage to vulnerable ecosystems. The fourth data set contains information on elevation and local slope, respectively. According to the slope, the relative cost is increased to account for construction challenges in regions with extreme slopes. The fifth data set contains land cover information. Here, areas covered by forest were allocated 25% higher costs due to the required creation of forest aisles and higher maintenance costs and 50% higher costs for regions covered by large water bodies, as this is a major barrier for grid construction.

The resulting weighted decision raster data set reflects the parameters described above and is used in the second step to calculate optimum connection pathways to extend the network to add unconnected clusters to that grid network. Optimum connection pathways, which reflect the lowest-cost path connecting all clusters, are identified by applying an MST approach [25]. An MST considers all possible connections and connects the locations by minimizing the required connections and costs of all new grid extension lines. This is required to achieve the least cost connection to minimize grid extension costs and transmission and distribution losses over long-distance grids. This leads to the least-cost grid extension.

Costs for grid extension can be calculated as total grid extension costs or be broken down to the costs per cluster of initial capital costs and operational costs. The calculation of the required capital expenditure for grid extension cost depends on the length of the new power line, transformer cost, and costs for the distribution grid. The length of the grid extension is derived from the optimum grid extension path; two transformers are assumed, one to connect to the existing grid and a second one to connect a distribution grid at the village level. The distribution costs at the village level are scaled according to the respective number of customers. The operational costs consist of power generation and maintenance costs. Individual costs for each parameter are shown in Table 4, which are based on discussions with the distribution companies, NERC, and other stakeholders.

The required power generation for the additional on-grid power supply is not modeled in this electrification planning tool. However, grid power generation and transmission costs are included based on the projected demand of each cluster in $/kWh plus the national generation and transmission costs, although the amount of power generation capacity and investment needed is not be determined. Thus, it must be kept in mind that the modeled grid extension pathways should only be implemented if power generating capacity is equally increased with sufficient network capacity.

Table 4 Assumptions for Grid Extension Costs

Category	Costs
Medium voltage grid	20 000 $ / km
Transformer station (1.5 times peak demand, 2 transformer stations per cluster)	100 $ / kW
Connection distribution grid	400 $ / customer
Central power generation and transmission (including 11 % transmission losses)	0.08 $ / kWh
Project development costs	20 000 $ / project

E. Least-Cost Planning—What Is the Optimized Phase-Wise Electrification Plan to Implement Those Options?

After calculating the electricity needs and costs of potential supply options for each cluster, a final electrification plan must be defined. This plan is based on a least-cost approach taking into account the current demand and supply situation of the central grid system and on a prioritization algorithm to assign the electrification options to different implementation phases. To assign the electrification options, a prioritization process is conductedas illustrated in Fig. 8.

The least-cost planning process assigns electrification options to all clusters based on different prioritizations and planning criteria. The first step is to identify all clusters for SHS. This is based on the assumption that for clusters with loads below 50-kW peak, private-sector-based minigrid development or grid connections are not economically feasible. Thus, all these clusters and the dispersed people are selected for electrification by SHS.

The second step of differentiating among minigrids and grid extension is more complex and requires the comprehensive modeling result from the prior steps. First, a final least-cost electrification plan is derived, which reflects the final layout of a 100% electrification based on LCOE comparison of minigrids and grid extension. As it is important for decision-makers to not only understand the final least-cost electrification plan but also the pathway to achieve it, certain prioritization criteria are introduced to assign electrification options along three implementation phases.

In the prioritization stage, very remote clusters for which grid-extension is not economically feasible based on the least-cost modeling are assigned as minigrids in all three phases.

For all other clusters, socioeconomic prioritization is conducted to foster minigrid electrification as an accelerated way of providing electricity in phases 1 and 2. The weighting and selection criteria for these clusters are chosen as following: size (weighted with factor 0.6), social infrastructure (schools + health facilities, factor 0.4), and distance to existing infrastructure (at least 5 km away from the grid). Based on these criteria, the minigrid clusters for rapid electrification can be chosen. These clusters can be transformed to interconnected minigrids if the grid extension is economically viable in a later electrification phases 2 and 3.

To determine the priority sites for grid electrification, clusters are bundled along certain grid branches based on the least-cost grid extension plan. Clusters, which need the least kilometer of grid line per kilowatt calculated electricity demand, are prioritized in the least-cost plan for grid electrification. If these clusters are already electrified by minigrids, they will be transformed to interconnected minigrids. These decision and prioritization processes help in determining a comprehensive least-cost electrification plan to achieve universal electricity access for the selected five federal states in Nigeria. All previously described modeling steps are necessary to determine the most cost-efficient and socially acceptable electrification recommendations along three implementation phases.

IV. RURAL ELECTRIFICATION PLANS—RESULTS FOR FIVE SELECTED FEDERAL STATES IN NIGERIA

A. Cluster Analysis and Energy Demand Modeling

For all five selected states, the presented electrification tool was applied to answer all four questions to derive an electrification plan along three phases. First, the question regarding the location of the (remote) population and electrification status was addressed. The cluster analysis was conducted resulting in 8048 clusters covering 21 million people, while 1.2 million people are dispersed and, therefore, not assigned to any cluster. Out of the 8048 clusters, 1381 clusters are connected to the existing grid. Although this covers only 17% of all clusters of the five states, the number of people living in these clusters amounts to 13.45 million (64% of the population). Hence, the grid connects the clusters with the highest population numbers (see Fig. 9) for population density versus grid-connection. The official electrification rate, which is on average approximately 50% for the five states, reveals that there are also people without access to energy living in the grid-connected clusters. These people can be served by grid densification as the central infrastructure is already very close.

By applying the elaborated demand projection model for each consumer cluster, a detailed load profile (8760 values) reflecting 1 year comprised of the site-specific demand is created. This profile can serve as one of the input data sets for the cost assessment of electrification options. For a total of 6667 nonelectrified villages with a population of 7.5 million, we identified an overall peak demand of 590 MW and an annual electricity consumption of 1150 GWh for these consumers under the assumed socioeconomic conditions (compare Table 5).

Table 5 Results of Load Projection of Rural Electricity Demand

State	Clusters	Rural population (in million)	Peak demand (sum in MW)	Energy consumption (sum in GWh)
Cross River	544	0.79	96.5	192.5
Niger	2,238	2.01	140.0	276.8
Ogun	992	0.95	67.3	136.0
Plateau	1,645	1.83	132.3	255.1
Sokoto	1,248	1.96	154.1	290.0
Sum	6,667	7.54	590.2	1,150.4

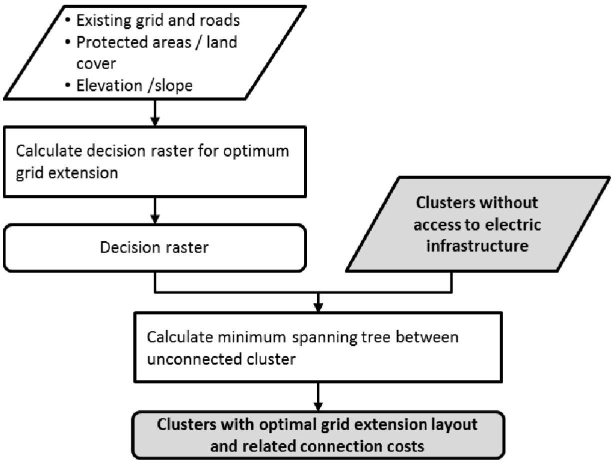

Fig. 7. ***Flowchart of grid extension modeling.***

The calculated demand of grid-connected clusters adds up to a peak demand of 1244 MW for the case of complete grid-connected clusters in the five states. For the entirety of Nigeria, only 4 GW of operating on-grid power generation capacities are available. Comparing this with the 1.24-GW demand of the five states, which constitutes only 12% of the Nigerian population, reveals the enormous lack of supply capacities in this country. This leads to the conclusion that any electrification plan for Nigeria has to include an off-grid electrification phase as an immediate solution so that the on-grid capacities can be increased to connect new customers to the central grid.

B. Least-Cost Minigrid and Grid Extension Modeling for Least-Cost Plan

Using the demand values as the baseline, the detailed minigrid and grid extension modeling was applied. This signifies that for each cluster, a detailed sizing of a potential minigrid was performed as well as an optimal grid

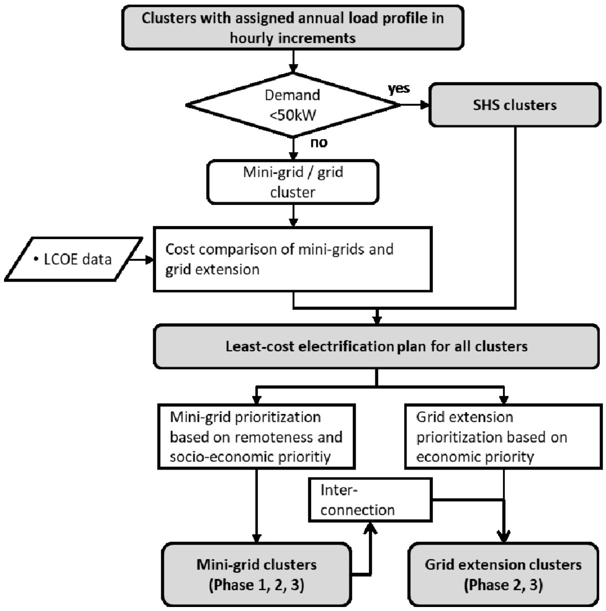

Fig. 8. ***Flowchart of phase-wise least-cost electrification planning.***

extension pathway was calculated to understand the LCOE of both supply options.

Minigrid modeling for each cluster leads to the following results: 383-MW PV, 859-MWh battery, and 339 diesel gen-

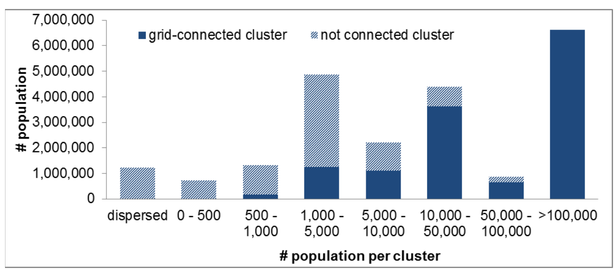

Fig. 9. ***Population distribution and status of grid connection for all identified clusters.***

Table 6 Results for Minigrid Modeling of All Not Connected Clusters

State	PV size [MW]	Battery size [MWh]	Generator size [MW]	LCOE [USD/kWh]	RE Share [%]	Investment [M USD]
Cross River	83	171	67	0.56	67	336
Niger	76	170	68	0.54	69	333
Ogun	47	96	39	0.55	64	190
Plateau	79	177	69	0.55	69	356
Sokoto	99	245	96	0.54	72	473
Total	383	859	339	0.55	68	1,687

erator capacities would be needed to supply all clusters with isolated minigrid systems in a technoeconomic least-cost way. Specific values per state can be obtained from Table 6.

The average RE-share would be 68% and $1.7 billion investments would be needed. LCOE is relatively high due to the high diesel costs, the high evening peak requiring large battery capacities, and the high costs for the distribution grid per customer.

Grid extension modeling results can be differentiated in the number of newly connected clusters and in the number of new grid branches. A grid branch is a new fork branching off the existing grid and connecting one or more clusters on its pathway. Grid extension measures are suggested to be implemented in phases 2 and 3, after the existing grid may be strengthened to cover the actual load and provide capacities for grid extension. Grid extension modeling results (Table 7) are influenced by various characteristics of different federal states: states, which cover a larger area and are subject to lower population densities (e.g., Niger and Sokoto), require longer distance grid extensions compared to the smaller, more densely populated states such as Ogun and Cross River. Also, these two southern federal states have already the highest

Table 7 Grid Extension Modeling Results for the Five Selected Federal States

Phase	State	Cross River	Niger	Ogun	Plateau	Sokoto	Total
2	# connected cluster (mini-grids)	114 (38)	115 (22)	82 (23)	149 (29)	145 (54)	605 (166)
	# connected branches	64	68	47	62	76	317
	km of line	450	926	390	625	720	3,100
3	# connected cluster (mini-grids)	158 (82)	227 (103)	74 (81)	175 (182)	177 (156)	811 (604)
	# connected branches	64	69	46	65	78	322
	km of line	833	2,340	969	2,262	2,075	8,450

Table 8 Number of People Gaining Energy Access by Different Supply Options—Phase 1

State	Grid densification		Mini-grid		SHS	
	#people	MW	#people	MW	#people	MW
Cross River	552,000	75	307,000	30	88,000	1.3
Niger	76,000	6	583,000	33	348,000	3.0
Ogun	237,000	20	323,000	18	149,000	1.2
Plateau	481,000	43	517,000	28	246,000	2.3
Sokoto	606,000	87	690,000	39	175,000	1.8
Total	1,952,000	231	2,420,000	148	1,006,000	9.6

connection rates compared to the other states; therefore, less novel kilometers of grid extension lines are suggested. For all five states, the modeling results are composed of more than 10 000 km of new MV grid lines. It is noticeable that the first grid extension phase requires less kilometers of grid compared to the second phase of grid extension, which is the consequence of the chosen phased least-cost electrification method, which is introduced in the following chapter.

C. Electrification Plan With Three Implementation Phases

After the detailed modeling of the LCOE of different supply options, the least-cost plan can be developed. The results of this least-cost electrification plan show a dominance of grid infrastructure in the long term, as the most economical solution for larger clusters. This is due to the dense population patterns and existing grid infrastructure in the states and the high efficiency of large networked infrastructure, if operated and maintained under sound conditions. Average supply costs—LCOE—for grid-connected clusters are \$10 per kWh lower than for those with minigrids. Nevertheless, significant shares of SHS are identified for the final plan for dispersed people and clusters with demand lower than 50-kW peak.

Three subsequent phases (Fig. 8) for implementation result from the application of the electrification planning tool, which begins by introducing decentralized electricity supply by minigrids in the first phase and includes the interconnection of off-grid minigrids to the central grid in stages two and three. Each phase is accompanied by the distribution of SHS for low-demand clusters and areas that are sparsely populated based on the least-cost layout. The three phases can be described as follows.

The startup phase—phase 1—emphasizes on electrification of priority clusters by minigrids with high RE shares. There is also an emphasis on off-grid minigrids that are to be deployed in remote areas and are planned to operate as off-grid systems for the foreseeable future. The central grid also requires reinforcement and densification as well as additional on-grid generation capacity. No grid expansion is suggested for phase 1, as the current infrastructure limitations would undermine actual gains due to the low quality of the central electricity supply in Nigeria.

Table 8 reveals the total number of people gaining energy access along different supply options with the related load. Niger state has the highest number and relative share of people provided by SHS and minigrids due to its large range. Cross River and Sokoto have the highest need of grid densification as they have a relatively widespread MV infrastructure, but low connection rates in the grid-connected clusters.

The intermediate phase—phase 2—assigns the second tranche of village clusters to off-grid minigrids and requires the expansion of branches from the central grid, provided successful progress of its restoration and energizing, new grid branches are integrated with several off-grid minigrids deployed during phase 1 and are not interconnected with the central grid. This is expected to help stabilize both voltage levels at the grid end. Detailed results can be found in Table 9. In the five states in phase 2 between 250 km (in Niger) and more than 700 km (in Sokoto), grid extension lines are accordingly required. Similar to the grid densification Sokoto has also the highest number of newly grid connected people. While, in total, only 50 MW of new off-grid minigrid capacities are developed in phase 2, 87 MW of minigrid capacities are interconnected to the central grid.

The completion phase—phase 3—leads to 100% of electricity access in the five states as shown in Table 10. It involves the interconnection with the central grid of most off-grid minigrids deployed during phases 1 and 2,

Table 9 Number of People Gaining Energy Access by Different Supply Options—Phase 2

State	Grid extension		Interconnected mini-grids		Mini-grid		SHS	
	#people	MW	#people	MW	#people	MW	#people	MW
Cross River	469,000	58	233,000	22	100,000	9	88,000	1.3
Niger	623,000	48	369,000	23	208,000	10	348,000	3.0
Ogun	311,000	24	153,000	9	109,000	6	149,000	1.2
Plateau	464,000	34	165,000	9	232,000	12	246,000	2.3
Sokoto	789,000	65	392,000	24	250,000	13	175,000	1.8
Total	2,656,000	229	1,312,000	87	899,000	50	1,006,000	9.6

thereby ensuring additional decentralized on-grid power generation capacity and local value generation from REs. Since the denser populated areas were already connected to the grid during phase 2, the length of additional grid lines is much higher than in the previous phase (minimum almost 1000 km in Ogun and about 2300 km in Niger). At this stage, the electricity supply system is expected to have developed into a modern, decentralized, and resilient power supply system.

With the restoration of the central grid in phase 1 and its expansion in branches ranked by economic efficiency in phases 2 and 3, the described solution shows the organic growth of a more decentralized power system in which off-grid minigrids and their RE-based power generation become interconnected with the central grid. Gaps in the evolving close-knit network are covered with the deployment of SHS for which efficient distribution approaches are required. An example of the spatial results is given in Fig. 10, and an interactive version of the results can be obtained at http://rrep-nigeria.integration.org/.

In summary, decentralized supply is defined by 225-MW PV, 504-MWh battery, and 196-MW diesel-based isolated and interconnected minigrids as well as by 29-MW SHS capacities. Thus, an overall share of REs of 32% is reached through decentralized and small-scale PV installations. Individual minigrid systems have on average approximately 60% RE-shares but can reach an RE share of up to 97%, primarily in the Sokoto, the state with the highest solar radiation of the year.

Investments of approximately $1600 million for MV and low-voltage distribution infrastructure, minigrids, and small-scale systems are required to achieve a 100% electrification rate. Investments necessary for building central power generation capacities to satisfy the currently suppressed demand together with the newly added demand have not been included in this modeling approach. Following the implementation of the above-outlined phases, the simulation results of the electricity system of the five states are characterized by an overall load of about 1804 MW, supplied via different electrification measures. About 1772 MW are covered from the central power generation through the central grid via 11 579-km new grid lines. Only a few RE minigrids with a total of 3-MW load remain isolated, while all others are interconnected to the central grid. At the end of the three implementation phases, all 22.2 million people in the five analyzed states are supplied by different electrification options. The total numbers per electrification option as well as the respective capacities are summarized in Table 11. In addition, the level of access in kilowatt per person is shown. It indicates lower per capita capacities for states with lower specific loads and higher SHS shares per household (e.g., Plateau State), while others show higher values based on high grid densification and grid extension efforts (e.g., Cross Rivers).

V. DISCUSSION

The location-specific modeling of electrification options and the subsequent derivation of a three-phase electrification plan for five Nigerian states allows gaining a superior understanding of the least-cost option and first estimation of requirements to achieve the targets as outlined in SDG7—to provide clean energy to all in the case study area.

For achieving a 100% electrification for the five considered states, a power generation with grid capacity of 1845 MW is necessary to meet the additional demand. For the final phase of our analysis, we find 93% of that capacity is to be provided through the central grid via grid connection and interconnected minigrids, 6.8% through SHS in remote clusters, and 0.2% through isolated minigrids. It must be underlined that several minigrids, which are implemented in phases 1 and 2 and grids supplying approximately 200 MW of load, are to be interconnected to the grid in phases 2 and 3. Therefore, renewable capacity from the minigrids contributes to the central grid, which,

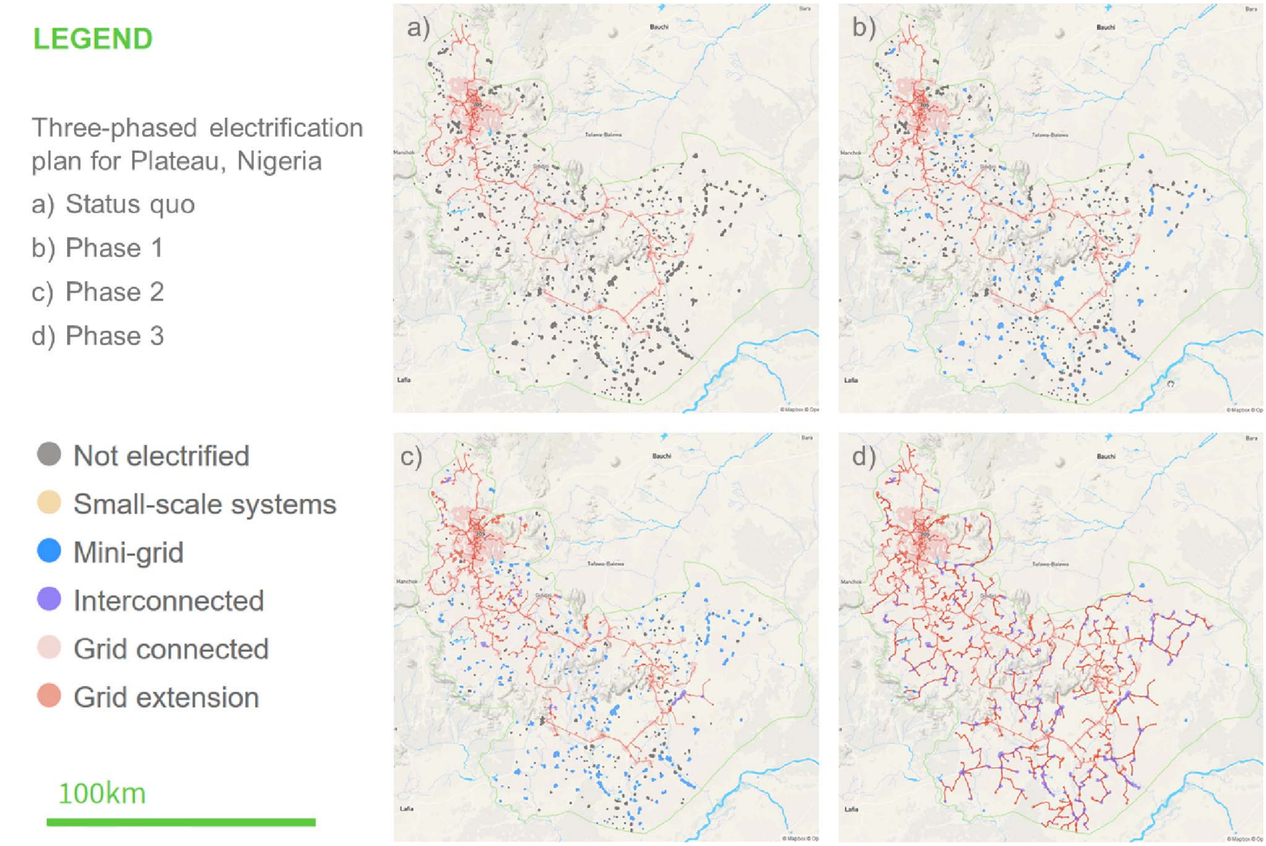

Fig. 10. ***Resulting three-phased least-cost electrification plan for Plateau State. (a) Status Quo. (b) Phase 1. (c) Phase 2. (d) Phase 3.***

however, would need additional capacity expansion to meet the additional demand from newly electrified areas. Looking at numbers of people served by different technologies, the share changes. 66% of share is supplied by new grid connection, grid densification, or interconnected minigrids, while 33% of share is served by SHS and 1% by isolated minigrids. This reveals that different service levels are provided by different electrification solutions leaving areas with SHS in lower supply levels. The dominance of grid electrification is consistent with two other studies focusing on electrification planning for entire Nigeria: Ohiare [36] identified 98% of nonelectrified communities viable for grid electrification, while the remaining 2% to be supplied through minigrids. In contrast to that, Mentis *et al.* [33] found a share of 85.6% for grid extension, 14.3% for minigrid supply, and 0.3% supply by SHS for the entire electrification of Nigeria. Our final minigrid share is similar to Ohiare while we identified a share of 30% for interconnected minigrids, which is higher than in both studies. This is a consequence of the applied phased approach, which allows more decentralized electrification. In addition, we identified a much higher share of SHS than in the other studies, which is based on the higher spatial resolution and the inclusion of dispersed people in the analysis who are not suitable for grid or minigrid-based electrification.

Details on the demand for electricity, the required power supply and technical setup as well as the related necessary investments were unknown, and our study sheds the first light on them. These numbers shall help local stakeholders to better understand the overall requirements to improve the national planning processes and substantiate figures with concrete modeling results.

The intent of this analysis is to provide a first rough estimation on a prefeasibility level by curtailing the level of detail in each of the four steps. This provides a robust basis for the preliminary analysis of results to guide the next level of detailed plans for implementation. In particular, the following limitations are suggested to be overcome in more detailed assessments.

VI. LIMITATIONS AND FUTURE RESEARCH NEEDS

The derived population cluster, which forms the basis for further electrification planning, is based on population data sets derived from satellite imagery. These data sets are limited in their spatial resolution, and in some cases, certain areas are misclassified as being populated, as well as in other cases, populated areas remain undetected. Furthermore, a threshold was defined in order to delineate the settlement borders to form villages. This affects the size and the number of derived clusters. Future analyses should

Table 10 Number of People Gaining Energy Access by Different Supply Options—Phase 3

State	Grid extension		Interconnected mini-grids		Mini-grid		SHS	
	#people	MW	#people	MW	#people	MW	#people	MW
Cross River	255,000	32	174,000	17	0	0	90,000	1.3
Niger	610,000	41	378,000	18	15,000	1	349,000	3.0
Ogun	386,000	27	279,000	15	0	0	150,000	1.3
Plateau	865,000	63	576,000	31	4,000	0	250,000	2.3
Sokoto	835,000	63	536,000	28	4,000	0	175,000	1.8
Total	2,951,000	226	1,943,000	109	23,000	1	1,014,000	9.7

include more ground trothing exercises such as remote mapping of buildings as conducted by OpenStreet Map in or new open data sets [26].

To assign the status of electrification to each cluster (yes/no), existing high and MV grid data were used and combined with night light satellite imagery. These data sets were also be limited in their accuracy and current status. In addition, decentralized energy supply by diesel gensets may be wrongly defined as grid connected. Constant efforts on collecting real grid extension data can overcome these limitations.

The developed load projection model is capable of assessing site-specific rural electricity demands but still has limitations. The model can consider several different consumer groups with individual demands and profiles. The input parameters are mainly based on literature research and validated in stakeholder workshops. Future improvements should be based on more ground-truthing of data via empirical field research combining, for example, surveys with GIS-based extrapolation [5]. In addition, load dynamics such as the influence of early electrification, changing tariffs, and migration patterns should be included in the future to predict the demand not only as static value but also as dynamic along the electrification phases.

Based on the cluster and load analyses, the electrification options were modeled. Despite having a very detailed minigrid sizing and grid extension model, limitations still exist. For the clusters assigned to electrification by SHS, no distinction was made between

Table 11 Final Results After Implementation of Electrification Plans

Category	Details	Cross River	Niger	Ogun	Plateau	Sokoto	Total
# of people in thousand	*Already connected*	*2,000*	*2,600*	*3,600*	*1,500*	*1,800*	*11,500*
	Densification	*552*	*76*	*237*	*481*	*606*	1,952
	Grid extension	*724*	*1,233*	*697*	*1,329*	*1,624*	5,607
	Intercon. mini-grids[1]	*407*	*747*	*432*	*741*	*928*	3,255
	Isolated mini-grids	-	*59*	-	*12*	*16*	87
	SHS	*266*	*1,045*	*448*	*742*	*525*	3,026
	Newly electrified (total)	**1,542**	**2,413**	**1,382**	**2,564**	**2,771**	**10,672**
Demand / capacities in MW	*Already connected*	*283*	*206*	*298*	*132*	*167*	*1,086*
	Densification	75	6	20	43	87	231
	Grid extension	90	89	51	97	128	455
	Intercon. mini-grids[1]	39	41	24	40	52	196
	Isolated mini-grids	-	3	-	0	0	3
	SHS	4	9	4	7	5	29
	Total new capacities	**452**	**313**	**373**	**279**	**388**	**1,804**
Level of access (avg.) in kW/cap		**0.13**	**0.06**	**0.07**	**0.07**	**0.10**	**0.09**
Total investments in M USD		**300**	**363**	**194**	**370**	**351**	**1,578**

households with different abilities to pay or ownership of different appliances. This means if more knowledge on demand on household level was to be available, SHS can be assigned more cost-effectively along different Tier levels depending upon the needs of the consumers.

Currently, the minigrid model is designed to deliver 100% of the demand via PV-battery–diesel systems. This high quality of supply does not necessarily reflect the reality of need or feasible consumption patterns or real demand (cf. [28]), and a more flexible supply model would lower the costs of minigrids by allowing a fraction of demand served for example only 95%.

The grid extension modeling has a strong focus on the optimization on the topographical grid layout and the optimum connections based on all sites. The model does not consider electrotechnical limitations yet, such as the capacity in the existing grid as well as line losses in relation to the total length of line and the respective voltage levels. Thus, future planning tools should include a modeling of the grid capacities and the impact of connecting new clusters on the central system.

A phase-wise electrification approach was chosen to consider the temporal effects of electrification and interconnection of minigrids to the central system. This approach is considerably more realistic than a snapshot of a least-cost 100% electrification plan. Nevertheless, the presented approach has still limitations. Due to missing data on investment budgets and policy targets, it is not possible to realistically estimate the timing of each phase. For further improvements, it is recommended to add feedback loops to the demand and supply model to reflect the changes in electricity supply of one phase toward the consecutive one.

Overall, it can be stated that the applied approach was helpful to sufficiently answer stated research questions with a sufficient level of confidence despite the poor quality or fundamental lack of data. It also helped in interactions and discussions with local stakeholder, which increased the local validity of input parameters and therefore the results. For future research, the approach will be made openly accessible and it is recommended that interdisciplinary and transdisciplinary groups jointly work on improving the approach: cluster identification, population, and access to energy assessments using satellite data can be improved with more detailed analysis methods incorporating machine learning. In addition, qualitative and quantitative real-world data harnessing potential fields of data agglomeration such as mobile phone surveys can largely increase the accuracy of assumptions. Future energy demand projections should focus extensively on the correlation between income and electricity consumption and incorporate socioeconomic transformation processes induced by energy access. Additional RE technologies besides solar PV should be analyzed based on the local availability of resources. However, most importantly, the electrotechnical feasibility of the projected grid extension should be investigated for future research work.

VII. CONCLUSION

In this paper, we present a novel approach for phased implementation of strategies for rural electrification planning that bridges the gap between the geospatial planning and the energy system modeling. The approach comprises the following steps: 1) localization of villages without electricity access; 2) projection of rural electricity demands; 3) identification of supply options and simulations; and 4) assessment of least-cost electrification strategies for implementation. The backbone of the approach is an automatized routine-based optimization on geospatial data and technoeconomic input parameter. The tool requires mainly globally available data sets to overcome the data scarcity for innumerable rural areas. Therefore, the model can be applied for developing electrification strategies for other regions of the world.

Least-cost electrification strategies for the five Nigerian states of Cross River, Niger, Ogun, Plateau, and Sokoto were developed based on the described approach. Applying the cluster analysis revealed 8048 clusters such as villages, towns, and cities in the focus states. Taking into account night light emissions and the spatial extension of the grid indicates that 17% of these clusters are connected to the central grid. As they represent more urban and peri-urban areas, they cover 64% of the population, but not all of them have access to electricity via the central grid and have to be electrified via grid densification in the future. For the remaining 6667 nonelectrified clusters (comprising 7.54 million people), a potential overall peak demand of 590 MW and an annual electricity consumption of 1150 GWh are calculated, which need to be served by different supply options. Finally, the simulation of these options underlines the cost-effectiveness of grid extension on the long term since grid-connected LCOE is mostly lower than minigrid LCOE in the analyzed Nigerian states due to high population densities and relatively low distances to the existing grid of the identified larger clusters (demand <50 kW). However, a stepwise electrification strategy is suggested: phase 1 includes the development of off-grid minigrid capacities for supplying priority clusters and the deployment of SHS for achieving a rapid electrification impact. For phase 2, the focus in on-grid extension and further off-grid minigrid development. Finally, phase 3 leads to 100% electrification and implies interconnection of most off-grid minigrids deployed during the earlier phases. Overall, the required capacity in minigrids exceeds 220 MW of solar, 500 MWh of lithium-ion battery, and 190 MW of diesel and further 29-MW SHS. Investments of approximately $1.58 billion for MV and low-voltage distribution infrastructure, minigrids, and small-scale systems are required.

Several important implications for policy and electrification planning can be derived from the findings of this study. Decentralized solutions such as minigrids have a crucial role as an intermediate solution for quick energy access in the case study states although interconnection to the grid must be considered for the long term. The importance of SHS increases, especially in sparsely populated areas, and needs to be included in any electrification planning. For sustainable electrification, both on-grid and off-grid sector plannings need to be harmonized and facilitated by clear regulation, especially if it comes to interconnection of minigrids to the central grid. As an example, minigrid development needs to be supported by addressing the risk of stranded assets after interconnection.

Finally, we believe that our work has achieved two goals. First, we developed a holistic planning approach and tools to derive realistic and cost-effective electrification recommendations even in situations with low-input data coverage. Second, the application of the tools resulted in clear recommendations to the local stakeholders on how to achieve 100% access to energy in the analyzed five federal states of Nigeria. ■

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