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ORIGINAL RESEARCH

Designing a nation-wide network of solar and wind-assisted parks for Nigeria and for Ghana

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Abstract The further development of sub-Saharan Africa is hinged on the possibility of the provision of uninterrupted power supply. Agriculture, education, and the economy in general are greatly affected by the power outage that has become difficult to comprehend. The energy system is inauspicious that only one in five inhabitant has access to electricity. Having electricity is necessary. Having access to clean energy is crucial. For example, a large number of people in Nigeria have electrical generators that release toxic fumes detrimental to the human health. Utilizing clean energy is considered the way of the future and to do that strategically locating the generating plants is important. Therefore, the introduction of solar parks (SPs) as well as solar and wind-assisted parks (SWAPs) on a wide scale is worthy of consideration since it yields an effective way of generating clean energy. This paper presents the application of a location model for SPs and SWAPs from a country's perspective. In particular, we focus on Nigeria and Ghana. The power supply infrastructure of both countries, as well as the policies surrounding the provision of off-grid energy are analyzed in depth. We present the advantages and disadvantages of two different methods (the grid approach and the problem owner method). We choose a hybrid approach by combining the grid and the problem owner method (POM). We apply the grid method to regions with high population density and utilize the POM for less populated areas. Furthermore, we take into account power plants that are operational or will be so in the near future. In the above fashion we design two separate, capacitated networks of SPs and SWAPs, one for Ghana, one for Nigeria. Each of these is powerful enough to cover—in a sustainable way—the energy requirement of the majority of households by a facility within reasonable distance.

Keywords Renewable energy · Location theory · Mathematical programming · Solar parks · Wind parks

Introduction

In Ikejemba and Schuur [1], a multi-step approach—including mathematical programming—was developed to design a capacitated network of solar parks (SPs) as well as solar and wind-assisted parks (SWAPs) (i.e., parks that generate both solar and wind energy) in South-Eastern Nigeria, taking into account geographical and demographical characteristics. The present paper extends the application of the SWAP model to a country's perspective. Here, we focus on Nigeria and Ghana. Let us start by defining some key notions. Next, in "Generic concepts for selecting potential locations" we introduce generic concepts that are used throughout the paper. We present the advantages and disadvantages of the grid method (used in Ikejemba and Schuur [1]) and the so-called problem owner method (POM, see below) and their consequences on the energy status in Africa.

Definitions:

Grid method (*GM*): The GM in this context is a method whereby potential locations are selected from points on a 2-dimensional $m \times n$ grid graph $G_{m,n}$. In addition, it may be described as a greenfield method, whereby the options of selecting potential locations are not constrained by a public office or a problem owner.

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Problem owner method (*POM*): The POM in this context is a condition or a state, whereby the potential locations considered are provided by a public office, a third party or an individual. It may be considered as a brownfield method such that the potential locations are selected from any existing locations.

Micro-grid: A micro-grid is a miniature power generation grid that can operate independently (off-grid) or in concomitance with the area's main electrical grid (on-grid).

Off-grid energy: Off-grid energy is energy that is provided by micro-grids to villages and communities that are—generally—not connected to the main electrical or national grid.

On-grid energy: On-grid energy is energy that is provided by national or main electrical grid.

Smart grid: Special case of a micro-grid where communication technology and digital information are utilized to control and optimize the grid in real time.

Generic concepts for selecting potential locations

The importance of selecting appropriate locations when designing SWAPs is high. This indicates the line that defines either the success or failure of the project. It provides more efficient service and reduces the cost of power transportation and complications. At an interview carried out with several decision-makers in the field of renewable energy (RE) in sub-Saharan Africa (private communication [2]), a vast majority did not consider the issue of determining optimal locations when installing solar PV smart or micro-grids.

However, in the aspect of wind energy, determining the appropriate locations is important as the direction of the wind is essential. Nevertheless, more than 80 % of the interviewees claim the only data they utilize in determining the appropriate locations is retrieved from the meteorological department. The interview response shows that the population, household distribution, community usage data and several relevant characteristics are not taken into consideration. It is known that many solar and wind energy projects in Africa fail due to miscalculations, inappropriate location selection, investor scare, vandalism, theft and mismanagement of the resources. The number of failed renewable energy projects in Africa over the last 20 years is unacceptable, and verging on the irresponsible. These failed projects have set back development by raising aspirations and then failing to deliver. Particularly in sub-Saharan Africa, the electric utility infrastructure necessary for large-scale renewable energy power plants is lacking, which leads to underdevelopment and poverty.

There are, however, multiple methods for selecting potential location(s) for SWAPs, micro-grids or energy generation systems, such as the *grid method* (as utilized in [1]) and the *problem owner method*, whereby the problem owner presents own potential location(s). Both methods have advantages as well as disadvantages.

Advantages of the grid method:

- Takes into account all possible potential locations, albeit within a grid structure.
- Directly takes into account geographical and demographical characteristics.
- With the GM, performing sensitivity analysis is straightforward; so as to assess the impact that changes in a certain parameter (grid dimensions) will have on the conclusions of the experiment.
- Utilizing the GM and our mathematical model, we are able to minimize the number of facilities required, based on the demographical and geographical characteristics of the target area.
- Requires less study towards application.

Disadvantages of the grid method:

- Requires a considerable amount of time to design and determine the appropriate dimensions of the grid. Sensitivity analysis can, however, be executed to assess the impact that changes in grid dimensions will have on the findings of the model.
- Variability in dimensioning grid.

Advantages of the problem owner method:

- Direct availability of potential locations.
- Computation times are short.
- Maximum control.
- Multiple changes can be implemented and experiments can be carried out in shorter periods of time.

Disadvantages of the problem owner method:

- Does not take into account all possible/potential locations.
- Probability of omitting better potential locations. However, this can be curbed by executing an extensive initial study.
- The number of facilities is dictated and does not necessarily represent the required number when we impose the constraint that every demand location is within a pre-specified distance from a facility.
- The POM mainly focuses on the size of facilities and may not necessarily consider the requirement of the communities surrounding the facilities.

Given the absence of modern structural and urban planning in most African cities, villages and communities, it is important to select the appropriate locations for facilities so as to promote the conservation of natural reserve. However, in such situations of underdevelopment the difficulty in selecting appropriate locations intensifies.

In the present paper we design two separate, capacitated networks of SPs and SWAPs, one for Ghana, one for Nigeria. Each of these is powerful enough to cover—in a sustainable way—the energy requirement of the majority of households by a facility within reasonable distance.

The remainder of the paper is structured as follows: "Related work" presents an overview of relevant literature. In "Model variations", we discuss variants of the SWAP model. In particular, we describe the fewest facilities model, yielding the smallest number of facilities enabling near-coverage of total demand. Starting from that smallest number we introduce models for further optimization. We do so both for the grid method as well as for POM. In "Power supply infrastructure and SWAP options in Nigeria and Ghana" we analyze the current energy situation in Nigeria and Ghana, respectively. In addition, the policies surrounding the provision of off-grid energy (micro-grids) are discussed. In "Solution approach", we present our solution approach where we also develop new methods, variants and extensions of our model and discuss their application to Nigeria and Ghana. We take into account additional characteristics such as existing and future/planned power plants and population characteristics per local government area. In "Bringing our solution method to practice", we implement our solution approach to determine the appropriate locations for solar parks (SPs) and solar and wind-assisted parks (SWAPs). In "Conclusions and further research" we present a discussion of the findings of our solution approach and experiments and finally, we present the recommendations and conclusions to the paper.

Related work

Research on location theory started in the early 1900s when Alfred Weber examined how to locate a single warehouse such that the total of all distances between the warehouse and customers is minimal [3]. Following this embryonic study, location theory was driven by some applications which inspired researchers from different fields of study. The development and investment in a new facility such as a micro-grid or an off-grid energy system, is typically expensive and a time-delicate project. Before a facility can be established, candidate sites must be identified, suitable capacity specifications must be determined for the facility, and large amounts of capital must be assigned. While the main aim driving the location of such a system is dependent on the individual firm or government, the soaring costs associated with this action make almost any location-allocation project a long-term investment. Thus, SWAPs which are positioned today are anticipated to be running for a long period of time. Natural changes during the life-span of the facility can drastically affect the interest of a particular location, twirling today's optimal location into an investment disaster. Therefore, establishing the best sites for new SWAPs is an important strategic challenge [4].

In the field of Operations Research, researchers have created a vast number of mathematical models to solve a wide range of location-allocation problems. A number of different objective functions have been devised to make such models applicable to different situations. Regrettably, the produced models can be difficult to solve to optimality [5]. The computational difficulty presented by intricate location models has, until lately, limited most study in this realm to fixed and deterministic problems. In the latter, all inputs such as time, distances and demands are known quantities and outputs are cited as zero–one decision values [6]. While such problems can provide users with awareness about generic location selection, modeling the uncertainties that are important in making real-world decisions is impossible for these models. In locating micro-grids and off-grid energy (SWAPs)—providing either private or public utility services—it is critical to assure that the selected location sites serve the cause of minimizing community cost or maximizing the benefits for the habitants. Likewise, the capacity allocation to these SWAPs possesses a direct impact on the system's efficiency as a whole.

The formulation of the location-allocation model represents an important role in energy utility planning, as it yields a framework for exploring problems with regards to accessibility, differentiating the caliber of previous location decisions, and providing several solutions that change and improve the existing system [7]. A crucial issue highlighted during the course of this study is the selection of a suitable objective function or measure. Formulating the objective function highly depends on the ownership of the SWAPs, both whether private or public and the condition of the SWAPs, as has been earlier mentioned [8].

In addition, if we compare private to public, private SWAPs are often cited to achieve stated organizational objectives, such as maximize profit or minimize cost. Contrary to private SWAPs, the goals and objectives of public SWAPs are more strenuous to realize. However, various possible criteria (objective functions) exist when viewed from the perspective of location theory. The problem owner is left to make the decision that aligns with the proposed goal of optimizing profit, cost or public service as the case may be. Furthermore, note that a vast amount of recent literature exists for locating wind park facilities, but, to the best of our knowledge no paper currently exists that discusses selecting the appropriate locations for SWAPs or Solar Parks in sub-Saharan Africa as this is important from the perspective of designing a sustainable energy future for developing countries. Ikejemba and Schuur take into account a sense of security based on distance by introducing a parameter D (maximum allowed distance for serving a household from a park), as well as transportation costs, demographical and geographical characteristics.

In the next section, we showcase the various types of location models and their applicability in locating SWAPs. Throughout the paper the following indices, parameters and decision variables are used:

General list of parameters and decision variables:

Indices:

$i =$ index of demand location, $\quad i \in I$;

$j =$ index of potential facility location, $\quad j \in J$;

Parameters:

$d_{ij} =$ the distance between demand location i and potential facility location j;

$D =$ maximum allowed distance for serving a demand location from a facility;

$V_i = \{ j | d_{ij} \leq D \} =$ set of potential facility locations within distance D from demand location i;

$p =$ the number of facilities to be located;

$h_i =$ demand at demand location i

Decision variables:

$$X_j = \begin{cases} 1 & \text{if a facility is allocated to a potential facility location } j, \\ 0 & \text{otherwise.} \end{cases}$$

$$Y_i = \begin{cases} 1 & \text{if demand location } i \text{ is (fully) served,} \\ 0 & \text{otherwise.} \end{cases}$$

$$Y_{ij} = \begin{cases} 1 & \text{if demand location } i \text{ is being served by a facility at } j, \\ 0 & \text{otherwise.} \end{cases}$$

Location models

In this section, we present and review different models with respect to location-allocation problems. In particular, we analyze the *Maximal Covering Location Problem* (*MCLP*) and the *Basic p-Median Model*.

Maximal covering location problem (MCLP)

The maximal covering location problem (MCLP) was first proposed by Church and ReVelle [9] and is one of the most familiar models utilized in the planning of public healthcare that seeks to maximize the population to be covered given a restrained number of clinics. An ample amount of research has been executed using MCLP to model facility locations and several techniques—from heuristics to exact methods—have been suggested to solve the problem. Several researchers such as Oppong [10], Batta et al. [11], and Li et al. [12] provide detailed descriptions of these models. Lately, the MCLP has been utilized to successfully solve larger problems with higher complexity and problems with more than one objective [13].

The MCLP aims to obtain the solution to the problem of locating facilities such that the coverage of demand for services within a given acceptable service distance is maximized. Since the MCLP has been shown to be combinatorially complex, a number of heuristics have been developed [14, 15]. Furthermore, the MCLP can be visualized as an alternative formulation of other well-known location models such as the location set covering model and the p-Median model [16].

This problem can be formulated in the following way:

$$\text{Maximize } z = \sum_{i \in I} h_i Y_i \tag{1}$$

$$\text{subject to: } \sum_{j \in J} X_j = p \tag{2}$$

$$\sum_{j \in V_i} X_j \geq Y_i \quad \forall i \in I \tag{3}$$

$$X_j \in \{0, 1\} \quad \forall j \in J \tag{4}$$

$$Y_i \in \{0, 1\} \quad \forall i \in I \tag{5}$$

The objective (1) is to maximize the number of people served or “covered” within the desired service distance. The number of facilities allocated is restricted to equal p in constraint (2). Constraints of type (3) allow Y_i equaling 1 only when one or more facilities are established at sites in the set V_i. Constraints (4) and (5) are binary requirements for the model variables.

The basic p-Median model

The basic p-Median model established by Hakimi [17] is one of the most favored models for locating public facilities [18]. According to Sleeb and McLaerty [19], it has successfully been utilized in controlling the outbreak of diseases. The model minimizes the distance between customers and facilities and can be formulated as follows:

$$\text{Minimize } \sum_i \sum_j d_{ij} Y_{ij} \tag{6}$$

$$\text{subject to: } \sum_j X_j = p \tag{7}$$

$$\sum_j Y_{ij} = 1 \quad \forall i \tag{8}$$

$$Y_{ij} \leq X_j, \quad \forall i, j \tag{9}$$

$$X_j \in \{0, 1\} \quad \forall j \tag{10}$$

$$Y_{ij} \in \{0,1\} \quad \forall i,j \tag{11}$$

The objective function (6) minimizes the total distance between demand locations and facilities. Constraint (7) ensures that exactly p facilities are opened. Constraint (8) stipulates that every demand location is assigned to precisely one facility. Constraint (9) authorizes assigning only to places at which facilities have been located. Constraint (10) and (11) are binary requirements for the model variables. A variation of the p-Median model is described as finding the location of p facilities such that the total demand-weighted distance between demand locations and facilities is minimized [20]. Constraints are as above, but the objective is in this case:

$$\text{Minimize} \sum_{i} \sum_{j} d_{ij} Y_{ij} h_i \tag{12}$$

This p-Median model is captivating since it captures the fact that as the combined weighted distance of travel is getting smaller, the more favorable it is for demand locations to be connected to the nearest facility. It has often become a norm that the use of facilities decreases expeditiously when the time for customers to reach these facilities exceeds a specific time. According to Rahman [21], this is the norm with the use of certain facilities in rural areas in developing states.

Model variations

Policy makers or public officials (e.g., using the POM) may have different objectives than those that can be obtained with the SWAP model [1]. These objectives may lead to variants of the SWAP model, with different constraints and/or objective functions. We therefore examine model variations to provide solutions to problems with different objective functions that may exist in locating SPs and/or SWAPs. The following two questions are crucial:

Q1: What is the smallest number of facilities for which almost all the demand locations have a connection to the selected facilities within a distance limit D?

Q2: Given a fixed number of facilities, how do we allocate the facilities optimally? Here, the word "optimal" may refer to different objectives, such as minimal total (weighted) distance, etc.

The fewest facilities model (FFM)

In this section we consider the question

Q1: What is the smallest number of facilities for which almost all the demand locations have a connection to the grid within a distance limit D?

"Grid variant" focuses on the grid context. Next, "POM variant" discusses the POM setting.

Grid variant

When working with a grid (as in Ikejemba and Schuur [1]), distances between potential facility locations and demand locations are easily generated. Thus, we may use the following model (which we refer to as FFM-grid):

$$\text{Minimize} \sum_{j \in J} X_j \tag{13}$$

subject to:

$$\sum_{i \in I} \sum_{j \in V_i} h_i Y_{ij} \geq \alpha \sum_{i \in I} h_i \tag{14}$$

$$\sum_{j \in V_i} Y_{ij} \leq 1 \quad \forall i \tag{15}$$

$$Y_{ij} \leq X_j \quad \forall i \forall j \in V_i \tag{16}$$

$$X_j \in \{0,1\} \quad \forall j \tag{17}$$

$$Y_{ij} \in \{0,1\} \quad \forall i \forall j \in V_i \tag{18}$$

Objective (13) minimizes the number of facilities needed. Constraint (14) ensures that a fraction α of the total demand is satisfied by facilities serving only demand points within a distance D. Constraint (15) stipulates that every demand point is at most assigned to one facility within the specified distance limit D. Constraint (16) authorizes power distribution only from locations—within a distance D—at which facilities have been located. Constraints (17) and (18) are binary requirements for the model variables.

POM variant

In the context of the problem owner method (POM), the concept of distances is no longer that useful anymore. Let us explain why. In the POM approach, the potential facility locations are provided by experts from the Ministry of Power. Actually, each of these POM locations is given by the ministry as a *sub-state* of one of the states. Since every potential facility location j is a sub-state, it makes sense to represent the demand locations as sub-states as well. In the same spirit, let us introduce for every demand location i the set:

$$\tilde{V}_i = \{j | j \text{ is adjacent to } i\}$$

which can be conceived as a topological equivalent of the set V_i introduced before. Here, "adjacent to" may mean "coinciding with" as well.

Now, to find the smallest number of facilities such that a fraction α of the total demand is satisfied by facilities serving only adjacent demand points, solve the integer linear programming problem FFM-grid from the previous section with V_i replaced by $\tilde{V}_i$. Let us denote the resulting integer linear program problem by FFM-POM.

Optimal allocation of a fixed number of facilities

Once we have found the preferred number of facilities from question Q1, it is crucial to allocate the facilities adequately. Hence the question:

Q2: Given a fixed number of p facilities, how do we allocate the facilities optimally? Here, the word "optimal" may refer to different objectives. Focusing on the grid variant, let us discuss three ideas:

- Idea 1: Maximizing the demand served with p facilities and distance limit D.
- Idea 2: Minimizing the total weighted transmission distance given a total of p facilities.
- Idea 3: Combining Idea 1 and Idea 2 as follows: (1) as first-priority goal maximize the demand served with p facilities and distance limit D (2) as second-priority goal minimize the total weighted transmission distance given a total of p facilities and given as constraint the maximal demand served that was obtained as first-priority goal.

Max h_i model

Idea 1: Maximizing the demand served with p facilities and distance limit D.

The model below is a proposed extension of the p-Median model. It deals with maximizing the service level in the case of a distance limit. In Owen and Daskin's [20] paper, models exist for which the maximum distance between demand locations and facilities is minimized. In this section, we incorporate a distance limit for transmission from a facility to a demand location. The objective function below maximizes the demand served with p facilities and D distance limit.

$$\text{Maximize} \sum_{i \in I} \sum_{j \in V_i} h_i Y_{ij}$$

The constraint below ensures that exactly p facilities are installed.

$$\text{subject to}: \sum_{j \in J} X_j = p$$

The constraint below stipulates that every demand location is at most assigned to a facility within the specified distance limit D.

$$\sum_{j \in V_i} Y_{ij} \leq 1 \quad \forall i$$

The constraint below authorizes assigning only to places at which facilities have been located within the distance limit D.

$$Y_{ij} \leq X_j \quad \forall i, \forall j \in V_i$$

The constraints below are binary requirements for the model variables.

$$X_j \in \{0, 1\} \quad \forall j$$

$$Y_{ij} \in \{0, 1\} \quad \forall i, \forall j \in V_i$$

The Max h_i model above always provides a feasible solution since it does not stipulate that all demands have to be met. Moreover, we know from FFM-grid, constraint (14), that the objective has a lower bound given by $\alpha \sum_{i \in I} h_i$.

Clearly, in a POM setting, to maximize the demand served with p facilities serving only adjacent demand points, one solves the above Max h_i problem with V_i replaced by $\tilde{V}_i$. Let us denote the resulting integer linear program problem by Max h_i-POM.

The minimum transmission distance model (MTDM)

Idea 2: Minimizing the total weighted transmission distance given a total number of p facilities. This is the variation of the p-median model discussed in "Location models" [20]:

$$\text{Minimize} \sum_i \sum_j d_{ij} Y_{ij} h_i$$

$$\text{subject to}: \sum_j X_j = p$$

$$\sum_j Y_{ij} = 1 \quad \forall i$$

$$Y_{ij} \leq X_j \quad \forall i, j$$

$$X_j \in \{0, 1\} \quad \forall j$$

$$Y_{ij} \in \{0, 1\} \quad \forall i, j$$

Combining the max h_i model with the MTDM model

Idea 3: Combine the Max h_i model with the MTDM model as follows:

$$\text{Minimize} \sum_i \sum_j d_{ij} Y_{ij} h_i$$

$$\text{subject to}: \sum_i \sum_{j \in V_i} Y_{ij} h_i = \text{optimal value of} \text{Max} h_i$$

$$\sum_j X_j = p$$

$$\sum_j Y_{ij} \leq 1 \quad \forall i$$

$$Y_{ij} \leq X_j \quad \forall i, j$$

$$X_j \in \{0, 1\} \quad \forall j$$

$Y_{ij} \in \{0, 1\} \quad \forall i, j$

Of course, one should be careful when executing the Max h_i or the combined approach, because it could potentially exclude coverage areas when dealing with a given p number of facilities. In situations where all possible households are to be covered, it is advisable to run the models with variations of p until the constraint $\sum_j Y_{ij} = 1$ holds.

Power supply infrastructure and SWAP options in Nigeria and Ghana

In Ikejemba and Schuur [1] a multi-step approach—including mathematical programming—was developed to design a capacitated network of SPs and SWAPs in South-Eastern Nigeria, taking into account geographical and demographical characteristics. In this section, we examine SWAP options for Nigeria and Ghana. We introduce constraints that take into account power stations, future plans/expansion of power stations, current solar facilities (if existing) and current wind statistics. Our research focuses on the design of SWAPs to support existing power infrastructure and to power off-grid communities. In addition, when designing SWAPs for off-grid communities and villages, the specific energy requirements are taken into consideration from surveys and interviews.

"Power supply in Nigeria" outlines the existing and future power supply infrastructure in Nigeria, as well as the options for renewable energy. The same is done in "Power supply in Ghana" for Ghana. "Comparing the power supply infrastructure of Nigeria and Ghana" compares the power supply infrastructure of both countries, as well as the consequences thereof for our approach.

Power supply in Nigeria

The Federal Ministry of Power in Nigeria indicated that the country's peak power generation as of late 2014 was approximately 3513.5 MW, against a peak demand of 12,800 MW. So, only 27 % of the peak demand was satisfied [22]. Nigeria is currently ranked as the third largest country without access to electricity by the International Energy Agency (IEA), whereas recent specialized research indicates that a 100 % steady power supply from renewable energy is conceivable in Nigeria [23]. The Nigerian Government is prone to produce, transmit, and disperse 35,000–40,000 MW of electricity according to the devised year 2020 goal which would entail a yearly investment of approximately $4 billion over a period of (presumably) 7 years [24]. However, the proposed paramount mover of this vault in generation is natural gas, ready to be saddled from Nigeria's tremendous reserves. As per the August 2013 Roadmap, the Federal Government of Nigeria aspires to expand energy production from fossil fuel sources to more than 20,000 MW by 2020. It is without doubt that Nigeria is blessed with adequate RE assets to meet its present and future development prerequisites. Be that as it may, the hydropower plants are the main sustainable resources currently being utilized. However, the inability of the hydro power plants to work at installed capacity is usually credited to subsequent causes such as: (1) seasonal variation in flow to the reservoir; (2) inter-annual variation in flow to the reservoir; (3) conflict among competitive uses; (4) sediment trapped in the reservoir; (5) upkeep and extra part issues; (6) insufficient fund; (7) human resources, and (8) strategy/policy issues [25].

Figure 1 shows where the main power plants (production) in Nigeria are currently located and also showcases the sizes of power generating plants per city in the country. This data is important in determining the appropriate location for SWAPs in Nigeria as illustrated on a smaller independent scale in Anambra State located in the south-eastern part of the country. As of December 2014, the total installed capacity of the power plants was 7445 MW. Available capacity was 4949 MW (2014 Year in Review, Presidential Task Force on Power, Pg. 53). Actual average generation was significantly less than 3900 MW. Almost all the gas-powered plants listed in Table 1 have considerable gas shortages due to constraints in supply, thereby adding to the impediment of power generation. There currently are 81 registered licensed power generating companies in Nigeria according to the Nigerian Electricity Regulatory Commission with power generation ranging from just 1 MW to approximately 3000 MW. However, it is difficult to track down on actual generation as over 50 % of the registered licensed organizations are off-grid and there is no federal or state infrastructure or system in place to determine which organizations actually generate power or how much power is actually being generated.

Figure 2 depicts the Nigerian power grid source indicating both the current principal power plants and the future planned installations. The figure also shows the transmission grids for both present and future. However, when we analyze the current status and future outlook of the transmission, we find that the current transmission capability is substantially less than 6000 MW for the whole country. More importantly, the current infrastructure has a significantly high technical loss, which in power transmission includes theft of electricity by felonious users spouting the transmission lines (as explained in Ikejemba and Schuur [1]), but is also attributed to poor equipment maintenance, planning and calculation mistakes, mismanagement of processes and accounting errors. In addition, the current transmission infrastructure has a low infrastructure coverage of less than 40 % of the population and a

Fig. 1 Power plants in Nigeria differentiated by plant capacity [45]

low per capita generation of less than 25 W [26]. Ikejemba and Schuur [1] indicate the high potential of solar energy in Nigeria and sub-Saharan Africa in general. Nigeria's geographical location is an advantage that facilitates energy generation from the sun in a large quantity. It is also important to note that if solar panels or modules were utilized to cover 0.01 of Nigeria's land area, the possibility to generate 1850 $\times$ 10^3 GWh of solar electricity per year is attainable; this is one hundred times more than the current grid electricity consumption level in the country [27].

Currently, wind energy is not utilized as part of the energy generation in Nigeria. What is accessible is artifacts indicating its past use. Be that as it may, the determination to implement a sustainable resolution to the energy crisis in Nigeria has provoked the legislature and additionally autonomous analysts to survey the country's possibilities for wind power generation [28]. Individual researchers on their part have made various assessments of potentials and availability to determine the magnitude of wind resources as shown in Ikejemba and Schuur [1]. Research activities on wind energy prospect in Nigeria, whatever the boundary of their uncertainties, have identified that extraordinary potential exists in wind energy for power generation in Nigeria. However, it is established that the wind speeds are frail in the southern part, except for the waterfront, coastal and seaward locations which are blustery. Offshore territories from Lagos through Ondo, Delta, Rivers, Bayelsa to Akwa Ibom States were accounted for to have possibilities for reaping solid wind energy throughout the year. Within the country, the wind speed in the northern region was reported as the strongest. Moreover, the mountainous landscape of the middle belt and northern border exhibit a high potential for substantial wind energy. It was, however, detected that, attributable to difference in topography and irregularity in landscape, sizeable differences may be present within the same area [29].

Most results [30] in the light of utilizing 40 years (1968–2007) accessible average wind information from the entire 44 wind stations covering the states of the country indicate that, the nation's wind jurisdiction is found to lie

Table 1 Power plant availability versus energy requirement for the highly populated 16 states

State	Power plant available? (yes/no)	Operational, partially operational, not operational	Peak plant size (MW)	Minimum energy requirement (MW)	Energy support coefficient	New SWAP required? (yes/no)
Lagos	Yes	Partially operational	1080	2344	0.46	Yes
Kano	No		N/A	2430	ESC < 1	Yes
Anambra	No		N/A	1053	ESC < 1	Yes
Rivers	Yes	Partially operational	624	1350	0.46	Yes
Kaduna	No		N/A	1557	ESC < 1	Yes
Imo	Yes	Non operational		1010	ESC < 1	Yes
Katsina	No		N/A	1477	ESC < 1	Yes
Akwa Ibom	Yes	Non operational		1014	ESC < 1	Yes
Oyo	No		N/A	1450	ESC < 1	Yes
Bauchi	No		N/A	1209	ESC < 1	Yes
Abia	Yes	Partially operational	118	714	0.17	Yes
Jigawa	No		N/A	1105	ESC < 1	Yes
Ebonyi	No		N/A	549	ESC < 1	Yes
Benue	No		N/A	1083	ESC < 1	Yes
Ekiti	No		N/A	614	ESC < 1	Yes
Osun	No		N/A	879	ESC < 1	Yes

between inferior and average. The southern states have their average wind profile at 10 m height in the range between 3.0 and 3.5 m/s, contingent upon the states, and northern states fit with mean wind paces of between 4.0 and 7.5 m/s. This implies that Nigeria has great wind resources in almost all locations within the country. In spite of the fact that wind speeds in the southern states are low, they can be utilized for standalone SWAPs to generate power utilizing small-scale wind turbines [28]. This if utilized, will be a noteworthy leap forward for the country and sub-provincial territories not connected to the national power grid. However, given the technological advances between 2007 and 2015, it is possible to implement wind technology virtually in any location with minimal wind speed as current technology (*due to a confidentiality clause the names of the wind technology have been omitted*) utilizes minimum wind speed to generate adequate power to small villages and communities across sub-Saharan African countries.

Power supply in Ghana

Energy supply in Ghana has worsened over the years, impacting businesses, manufacturers, organizations and households vigorously, with regulators blaming the crisis on declined water levels in the dams coupled with gas shortage to power Ghana's thermal plants. In view of the strew of information, it is relatively arduous to acknowledge the actual installed capacity of power in Ghana. Nevertheless, a selection of facts and information indicates that it ranges between 2000 and 2800 MW with actual power availability falling between 1200 [31] and 2000 MW [32]. This serves a population of 25 million that is growing at 2.1 % per year. With a client base of roughly 1.4 million, it has been evaluated that 45–47 % of Ghana households, including 15–17 % of the rural communities, have access to grid power. All the regional capitals have been anchored to the national grid (see Fig. 3). This figure also shows the small and medium hydro resources in Ghana. Power utilization in the rural regions is assessed to be higher in the waterfront region (27 %) and forest (19 %) biological zones than in the savannah (4.3 %) regions of the nation. Urbanization in Ghana was anticipated to increase from around 40 % in 2000 to around 55 % in 2012 and in the long run to 60 % by 2020. Somewhat more than 33 % of the urban populace lives in Greater Accra and is relied upon to stretch around 40 % by 2020 [34]. An impressive amount of family spending goes into energy usage. Power sources in urban zones are more enhanced than in the rural regions, since access to different types of commercial fuels and machines is higher in the urban zones than in the country regions. Frequently the costs of power alternatives are higher in the provincial regions than in the urban areas where salaries are lower.

The government of Ghana have been seeking after a national energy policy. However, a large portion of the population stays without connection to the national power grid. It is exceptionally expensive to construct long-interval transmission lines to serve little groups, particularly when these groups are generally poor and cannot sustain to pay

Fig. 2 Nigeria's power grid source [present and future]—[46]

rates sufficiently high to take care of the expense of these power services. In addition, there is little to no verification of increased economic activities in areas or communities that benefited from the national electrification scheme [33]. Micro-grids (smaller scale power generation) and provincially installed generation systems such as solar panels, wind turbines, batteries and so forth can be more reasonable. In any case, it is expected that rural electrification will continue to be a challenge for the nation. The Minister for Power of the Republic of Ghana has, however, guaranteed the country that the power catastrophe would be over before the end of 2015 after various measures he said government was executing [31]. Then again, numerous individuals question the promise as this is not the first time government authorities have given such affirmations of ending the sporadic power supply going for a long time now. With the heightened power problems in the nation, government has opened up the area to permit private segment interest in power generation. In Ghana, the total installed generation capacity as of December 2010 was 2186 MW [35]. However, currently the estimated installed capacity is somewhat between 2000 and 2800 MW. This includes:

- The Akosombo Hydroelectric Power Plant with an installed capacity of 1020 MW. The Akosombo plant has been retrofitted with the replacement of the old turbine runners with new ones as well as electromechanical works aimed at restoring the plant to its original condition. The retrofit was completed in March 2005.

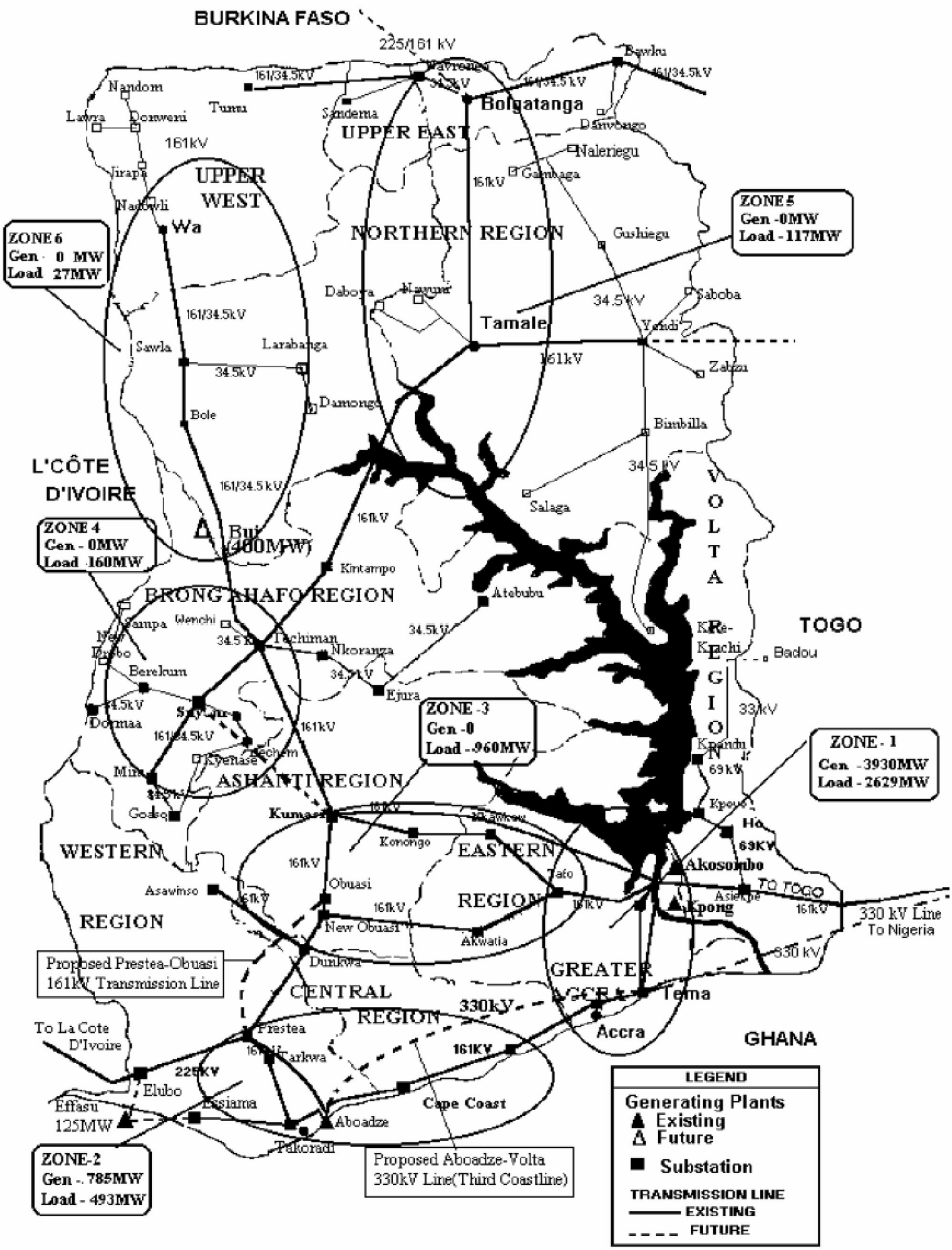

Fig. 3 Ghana grid power source [46]

- 160-MW Kpong Hydroelectric Power Plant.
- 550-MW installed thermal capacity at the Takoradi Thermal Power Station.
- 126-MW Diesel Power Plant at Tema 1 and 50 MW at Tema 2.
- 200-MW Sunon-Asogli (SAPP) thermal plant nd80-MW Mines reserve plant (MRP)

A 125-MW Power Barge "the Osagyefo Power Barge" is also available and is currently berthed at Effasu Mangyea in the Western Region with arrangements ongoing to establish viable fuel sources for it. The Osagyefo Barge was developed by the Ghana National Petroleum Corporation in order to utilize the natural gas available in the Tano oil and gas fields for power generation. The barge has been completed and is yet to go into commercial operation [33]. It is difficult to ascertain the clear number of power plants currently in Ghana because a substantial number of power plants are known to exist or forecasted, but the actual installed capacity and/or actual generation is unknown. Adding to the difficulty, as is the case in Nigeria, there are no mechanisms or infrastructure in place to account for updated data on the issues surrounding the power plants. However, a number of future thermal power stations and hydro-electric power stations have been planned for the country. This can be seen in Fig. 3. Until a couple of years back, there was minimal financial enthusiasm for creating power from scaled down hydro plants in Ghana, as an overabundance of inexpensive power from the hydro power facilities at Akosombo and Kpong was accessible. Therefore, a considerable number of the smaller hydro locales that were discovered suitable for advancement for the rural communities were not developed; and, starting now, some of these rural communities have either been connected with the main national grid or are within a couple of kilometers from the national grid [36]. Subsequently, the improvement of these communities for electrification has been debilitated impressively.

Just like Nigeria, Ghana is abundantly blessed with a plenty of renewable energy forms. It is among the nations in the Economic Community of West African States (ECOWAS) with tremendous renewable energy potential. All the major renewable energy resources like the sun, wind, biomass and hydro can possibly enhance the power generation for the nation. The average daily sun light level of the nation ranges from 4 to 6 kWh/m^2, with the most astounding potential happening in the northern part of the nation where the electrification rate is extremely low [37]. Wind speed over 6 m/s at a height of 50 m has been determined for some locations, indicating the feasibility for grid and off-grid power as well as for pumping water [38]. The largest photovoltaic (PV) project in Africa, the Nzema project, that is being designed to be situated in Ghana, is expected to provide electricity to more than 100,000 households [39]. The expected 155 MW plant will increase Ghana's electricity generating capacity by 6 %. Installation of more than 630,000 solar PV modules was expected to begin by the end of 2013 with electricity being generated early in 2014 and due to reach full capacity at the end of 2015 [39].

Nevertheless, this has not been the case as the US $350 million scheme has been delayed for unknown reasons usually faulted on the issues of funding and in turn delaying the project till 2017. This raises the hopes of businesses and individuals who hope to gain from the electrification and only to be let down by the delay caused. Based on a short interview and survey carried out in Accra (private communication [40]), a regular statement perceived from households in villages and communities is:

> "So many foreign companies and organizations visit us and carry out surveys on renewable energy and provide us with hopes of electrification. However, for so many years we have never heard from them and as such we are tired of hearing about development projects. We want the project to present itself".

Nonetheless, this does not affect the solar energy potential that Ghana possesses as is the case in Nigeria. It is the main goal of the Ghana power industry to have approximately 10 % of its energies generated from RE sources excluding large-scale hydropower by 2020 [41]. It is also without doubt that Ghana has great wind resources and locations of the high wind areas—such as the Accra Plains, Nkwanta, Gambaga mountains and Kwahu. These locations are similar to the locations in Nigeria with feasible wind potentials based on the technology utilized. The topmost energy that could be exploited from Ghana's available wind resource for power is estimated to be about 500–600 GWh/year according to the Arakis Energy Group [42]. To give an example—according to the Energy Commission of Ghana in 2011, the largest Akosombo hydroelectric power station in Ghana produced 6495 GWh of electricity and, including all Ghana's geothermal power stations in addition, total energy generated was 11,200 GWh in the same year [42]. However, these analyses do not take into account further constraint factors. Wind power in Ghana can possibly contribute altogether to the nation's energy industry giving the present advances in wind energy innovation. It is doable and conceivable to execute small-scale wind power generators to villages and communities with negligible wind possibilities. Constructive disposition of technologies for distributed energy generation in rural areas where the renewable energy resources are available can help quell the present energy crisis in Ghana as is the case with our research. Expansion of energy resources to incorporate renewable resources remains a key scheme of the government [43]. This presents high potential for grid and off-grid joint RE applications.

Comparing the power supply infrastructure of Nigeria and Ghana

The power supply infrastructure of Nigeria is quite similar to that of Ghana, albeit that Ghana has more hydro power in place. However, Ghana has a smaller population than Nigeria that is primarily concentrated in the highly populated areas. Consequently, we apply a simpler approach to Ghana than to Nigeria. In fact, we use only the grid method. In the sequel, we confine our methodological discussion to Nigeria. However, in the end, we present our final findings for both countries.

Solution approach

In this section, we present diverging potential solution approaches to be utilized in locating SWAPs so as to meet the energy demand of each of the two countries. We take into account geographical, demographical and meteorological characteristics.

Assumptions

In implementing our solution approaches we make the following assumptions:

1. The population within a specific state with power plants has priority to be served before power is exported out of the state (i.e., households with the closest proximity to the power plants are served first until the capacity of the plant is fully utilized).
2. Energy requirement per state is approximated based on the population and present and future energy plants of the country.
3. For states with power plant(s) meeting the energy requirement of the population no additional SWAPs are considered.
4. The population per sub-state is uniformly distributed.

Solution approach 1—grid approach applied cluster-wise

This solution approach is utilized for states with considerably high population density and no set of power plants meeting the energy requirement of the population within the state. The approach is similar to that utilized by Ikejemba and Schuur [1]. However, for this approach to work in the present context, it is important to demarcate the locations within the countries into *clusters* representing the states. For a specific cluster we proceed as follows:

Step 1: *Construct a longlist of potential locations for SPs and SWAPs.* To this end we place a suitable grid over the cluster. Each grid point is turned into a demand location by identifying the number of households around it. For potential SP locations, we take grid points that are compatible with current land use. For potential SWAP locations, we take grid points that—on top of that—have enough wind potential.

Step 2: *Construct a shortlist of potential locations for SPs and SWAPs. Stipulate that any of the facilities on this shortlist may only serve demand locations within a certain distance D.* In this step the longlist from Step 1 is reduced by taking into account the major and minor urban areas and the cost of transporting energy.

Step 3: *Solve an integer linear programming problem yielding a smallest subset of the shortlist (SPs and SWAPs together) such that almost all (say 95 %) of the overall energy requirement is covered.*

Step 4: *Solve an integer linear programming problem yielding a smallest subset of the SWAPs appearing on the shortlist from Step 2 such that a substantial part of the overall energy requirement is covered.* In this step we concentrate on SWAPs, since these parks are preferable to SPs.

Step 5: *Combine the subsets found in Step 3 and Step 4 and let the facilities that are close coincide.*

As in Ikejemba and Schuur [1], the model utilized in Step 3 as well as in Step 4 to execute the grid approach is given by FFM-grid (see "Grid variant").

Solution approach 2—POM approach

This solution approach is utilized for the collection S of states with low population density and no set of power plants meeting the energy requirement of the population within the state. We start off from a list of potential locations for SWAPs. Since the POM approach is used, these potential facility locations are provided by experts from the Ministry of Power. From this list consider the set $\tilde{J}$ of all those locations that are situated within one of the states of the collection S.

Recall from "POM variant" that each of these POM locations is given by the ministry as a *sub-state* of one of the states of S. Since every potential facility location j from $\tilde{J}$ is a sub-state, it makes sense to represent the demand locations as sub-states as well.

Now, to ensure that a fraction α of the total demand of all sub-states adjacent to a sub-state from $\tilde{J}$ is satisfied, solve the integer linear programming problem FFM-POM from "POM variant".

Bringing our solution method to practice

Focusing on Nigeria, we begin by analyzing the population of the states and extracting the top 10 states with the largest population. This is followed by further analysis on the states with a large population density. Amongst the 36 states in Nigeria only three states appear on both lists of most populated and with a high density. However, to reduce the number of demand locations and variables for our POM method (see "Solution approach 2—POM approach"), we opt to merge the list of most populated areas with the highest density, thus obtaining a total list of 16 states.

Next, for each of these 16 states, we verify whether a power plant is within the state and, if so, calculate the *energy support coefficient* (ESC), which is the ratio of the total energy provided by the plant to the total energy required by the state. However, it should be noted that as of May 2015, the Nigerian Electricity Regulatory Commission (NERC) reported that only five of the total power

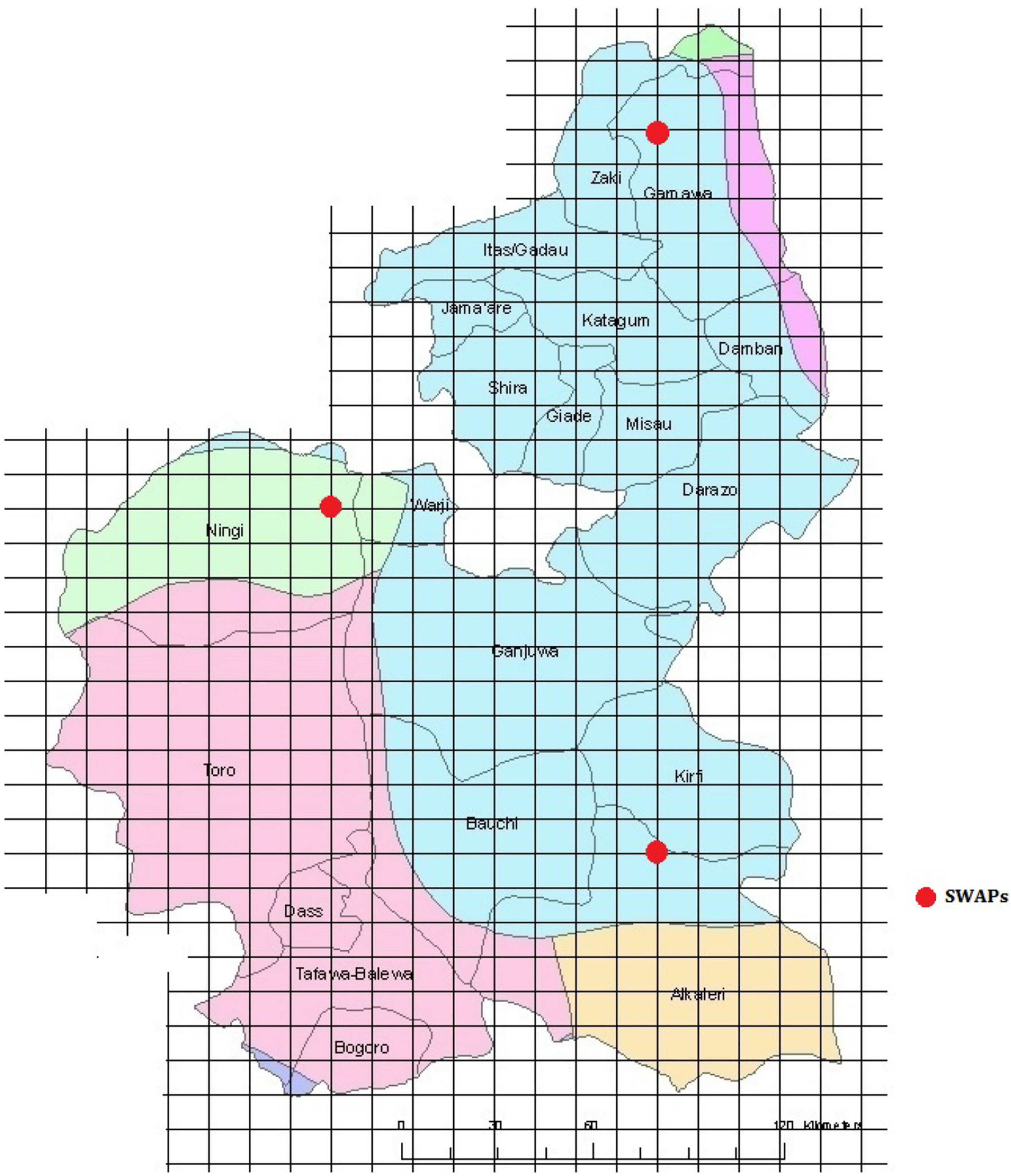

Fig. 4 Proposed SWAPs for Bauchi state

plants in Nigeria were functional. This has been attributed to the shortage of gas to the plants and water management problems at the hydro plants [44]. This fuels the need for the country to develop and implement renewable resources in a decentralized manner. From Table 1 it is clear that each of these 16 states requires a SWAP to help satisfy the energy requirement of the population.

Grid approach applied cluster-wise

In this section, we utilize the FFM-grid model for each of the 16 states considered highly populated and with a high population density. We solve the associated ILP (see "Grid variant") for various values of α around 0.7 using advanced integrated multidimensional modeling software. This is

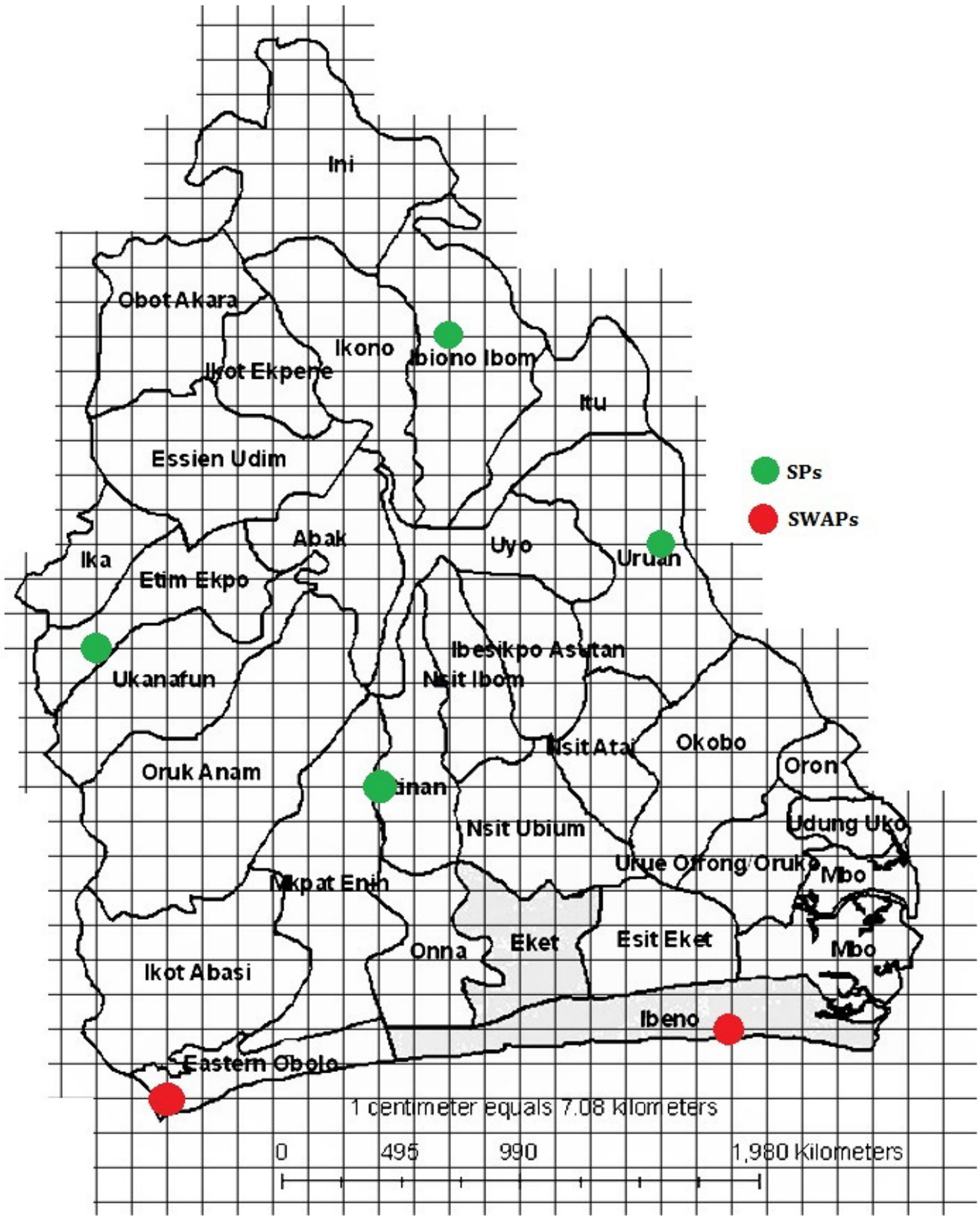

Fig. 5 Proposed SPs and SWAPs for Akwa Ibom state

Table 2 Selected facility locations for the highly populated 16 states

State	No. of selected locations	Energy requirement (MW)	Sub-state locations	Type	Size (MW)
Lagos	3	1264	Epe	SP	42
			Kosofe	SP	157
			Badagry	SWAPs	55
Kano	4	2430	Kibiya	SWAPs	102
			Dawakin Tofa	SWAPs	181
			Warawa	SWAPs	97
			Karaye	SWAPs	106
Anambra	6	1157	Nnewi South	SP	49
			Ihiala	SP	63
			Orumba North	SWAPs	36
			Onitsha North	SP	26
			Awka North	SWAPs	23
			Anyamelum	SWAPs	33
Rivers	1	726	Degema	SWAPs	146
Kaduna	3	1557	Kaura	SPs	82
			Ikara	SWAPs	92
			Giwa	SWAPs	138
Imo	2	1010	Ideato North	SPs	93
			Ohaji	SPs	109
Katsina	3	1477	Batagarawa	SWAPs	101
			Faskari	SWAPs	104
			Musawa	SPs	91
Akwa Ibom	6	1014	Etim Ekpo	SPs	30
			Ibeno	SWAPs	21
			Eastern Obolo	SWAPS	17
			Uruan	SPs	33
			Ibiono Ibom	SPs	54
			Etinan	SPs	48
Oyo	2	1450	Oluyole	SPs	207
			Olorunsogo	SPs	83
Bauchi	3	1209	Gamawa	SWAPs	72
			Toro	SWAPs	87
			Alkaleri	SWAPs	83
Abia	2	596	Arochukwu	SPs	79
			Ukwa West	SPs	41
Jigawa	3	1105	Biriniwa	SWAPs	65
			Ringim	SWAPs	88
			Garki	SPs	69
Ebonyi	2	549	Ishielu	SWAPs	54
			Afikpo South	SPs	56
Benue	3	1083	Oju	SWAPs	84
			Logo	SWAPs	85
			Apa	SPs	48
Ekiti	2	614	Ikole	SPs	62
			Ekiti South West	SPs	61
Osun	2	879	Odo-Otin	SPs	99
			Isokan	SPs	77

because given that the highly populated states have their inhabitants mostly clustered within an area it is easy to cover a higher number of the population with a low α value. The solution is rather insensitive to α and is given by the following set of parks as seen in sample Figs. 4 and 5 for Bauchi and Akwa Ibom state, respectively. Furthermore, Table 2 presents a compiled solution for each of the 16 states.

In Fig. 4 below, it can be seen that only SWAPs have been allocated to the state. This represents a feasible solution because Bauchi state is one of the states with an excellent wind potential in the northern part of the country. However, in Akwa Ibom state (see Fig. 5), a different scenario is obtained for both SPs and SWAPs. SPs have been indicated to perform better inland of the state. Although there is potential for SWAPs given the mean wind speed of the state, offshore SWAPs locations south of the state will be preferable.

The computational results for the rest of the high-density states can be seen in Table 2. The corresponding plant sizes are attributed to the population of the sub-state together with that of the surrounding sub-states. Let us clarify this. Suppose after solving the FFM-grid problem for a certain state we obtain Y_{ij}^* and X_j^* as optimal values of the decision variables. Then they cover two essential issues:

(1) the number of parks needed: $\sum_{j \in J} X_j^*$
(2) the required capacity F_j per facility j
(3) $F_j = \sum_{i \in W_j} h_i Y_{ij}^*$ where $W_j = \{\, i | d_{ij} \leq D\}$

So, when we aim for an energy coverage of 70 % in the highly populated states, then we need 47 facilities to accomplish this, of which 24 are SPs (so there is not enough wind), and 23 are SWAPs (enough wind). A mixture of SPs and SWAPs is not occurring, primarily because

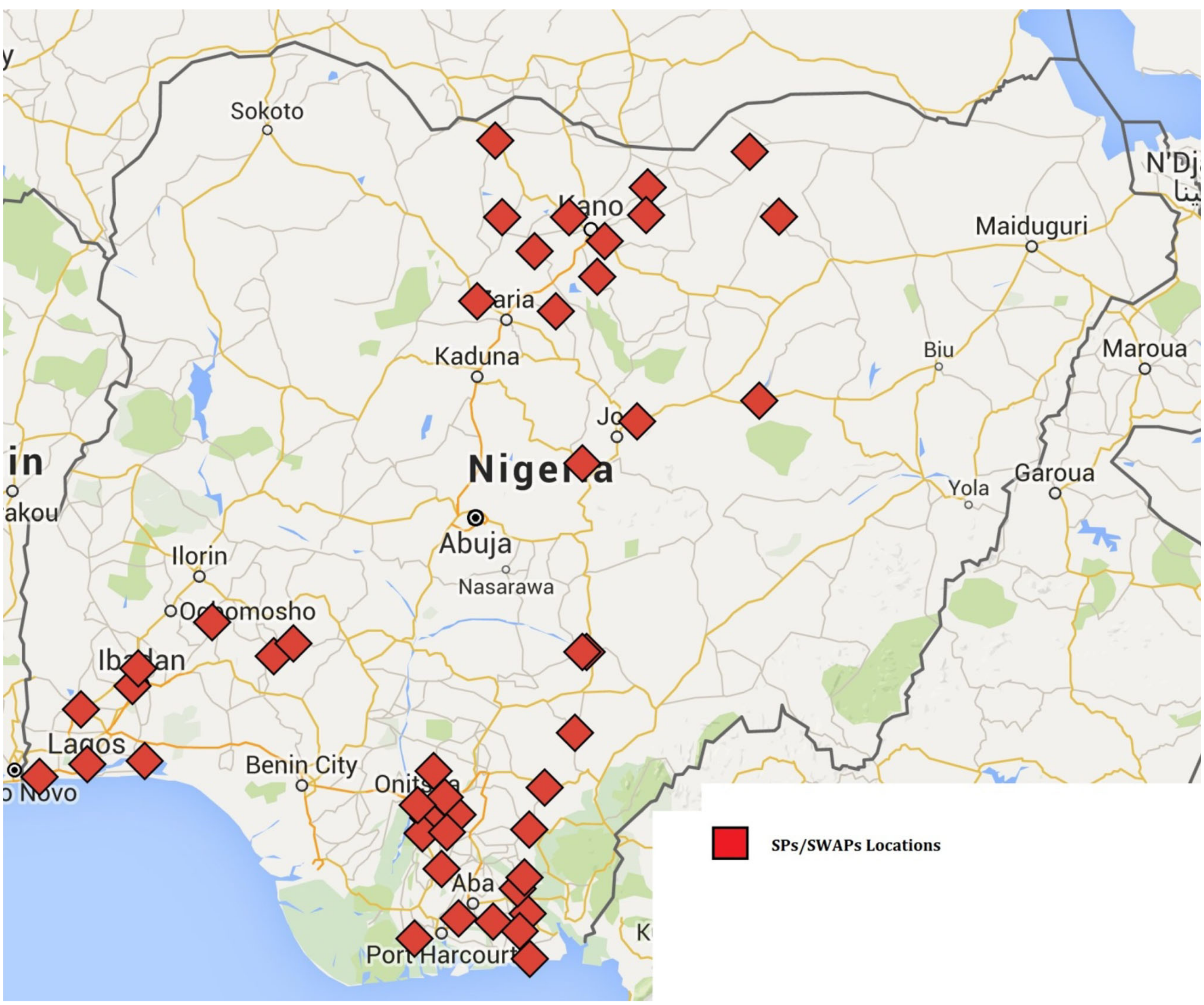

Fig. 6 Proposed locations for SPs and SWAPs for highly populated areas in Nigeria generating coverage of 70 %

of lack of space. Figure 6 shows the locations of these 15 facilities.

POM approach applied on the set of less densely populated states

In this section, we utilize the FFM-POM model for the rest of the 20 states not included in the previous experiment (i.e., the less densely populated states). However, in this case we carry out a two step-approach. Hereby, we initially utilize the FFM-POM model (see "POM variant"). Having obtained the minimal number (say p) of facilities needed, we use this number in the Max h_i-POM model to find the set of p facility locations that maximizes the demand covered.

We solve the FFM-POM problem with various values of α using the advanced integrated multidimensional modeling software. The output (i.e., the number of SPs and SWAPs to locate) based on the values of α can be seen in Table 3. Next, we execute the Max h_i-POM problem, the output of which is represented by whether a location is selected or not based on the result value of α.

Let us illustrate the interpretation of the table. Suppose, we aim for an energy coverage of 70 % in the lowly populated states then we need 15 facilities to accomplish this, of which six are SPs (so there is not enough wind), four are a mixture of SWAPs and SPs (so wind is moderate), and five are SWAPs (enough wind). Figure 7 shows the locations of these 15 facilities.

Main results for Ghana

For brevity of exposition, let us only briefly indicate our results for Ghana. For Ghana we used only the grid approach since Ghana has a smaller population that is primarily concentrated in the highly populated areas. Given that Ghana has numerous hydro-power plants running short of water, it is important that a backup system be introduced for those plants. However, small-sized SPs and SWAPs could be implemented in areas where power is unreachable

Table 3 SPs and SWAPs to be located for the 20 lowly populated stated for various values of α

State	POM locations	Location selected (yes/no)				Type	Size (MW)
		$\alpha = 0.6$ $p = 12$	$\alpha = 0.7$ $p = 15$	$\alpha = 0.8$ $p = 19$	$\alpha = 0.9$ $p = 21$		
F.C.T	Abuja	Yes	Yes	Yes	Yes	SWAPs	103
Kogi	Adavi	Yes	Yes	Yes	Yes	SPs/SWAPs	52
Ondo	Akure North	Yes	Yes	Yes	Yes	SPs	50
	Okitipupa	No	Yes	Yes	Yes	SPs	44
Taraba	Bali	Yes	Yes	Yes	Yes	SPs/SWAPs	51
Cross river	Biase	Yes	Yes	Yes	Yes	SPs	61
	Obudu	No	Yes	Yes	Yes	SPs/SWAPs	47
Nasarawa	Doma	Yes	Yes	Yes	Yes	SWAPs	55
Enugu	Enugu East	Yes	Yes	Yes	Yes	SPs/SWAPs	49
Edo	Etsako West	No	No	No	Yes	SPs	36
	Ovia North East	No	No	Yes	Yes	SPs	40
Ogun	Ewekoro	Yes	Yes	Yes	Yes	SPs	64
Yobe	Fune	No	No	Yes	Yes	SWAPs	41
Adamawa	Hong	No	No	No	No	–	–
	Jada	No	No	No	No	–	–
Kwara	Ilorin West	No	No	No	No	–	–
	Pategi	No	No	Yes	Yes	SPs	38
Plateau	Jos South	Yes	Yes	Yes	Yes	SPs	51
	Langtang South	No	No	No	No	SPs/SWAPs	27
Bayelsa	Kolokuma	No	No	No	Yes	SPs/SWAPs	36
Gombe	Kwami	Yes	Yes	Yes	Yes	SWAPs	59
Kebbi	Maiyama	No	No	No	No	–	–
Zamfara	Maru	Yes	Yes	Yes	Yes	SWAPs	52
Delta	Okpe	Yes	Yes	Yes	Yes	SPs	67
Sokoto	Sokoto North	No	No	Yes	Yes	SWAPs	36
Sokoto	Tambuwal	No	Yes	Yes	Yes	SWAPs	44

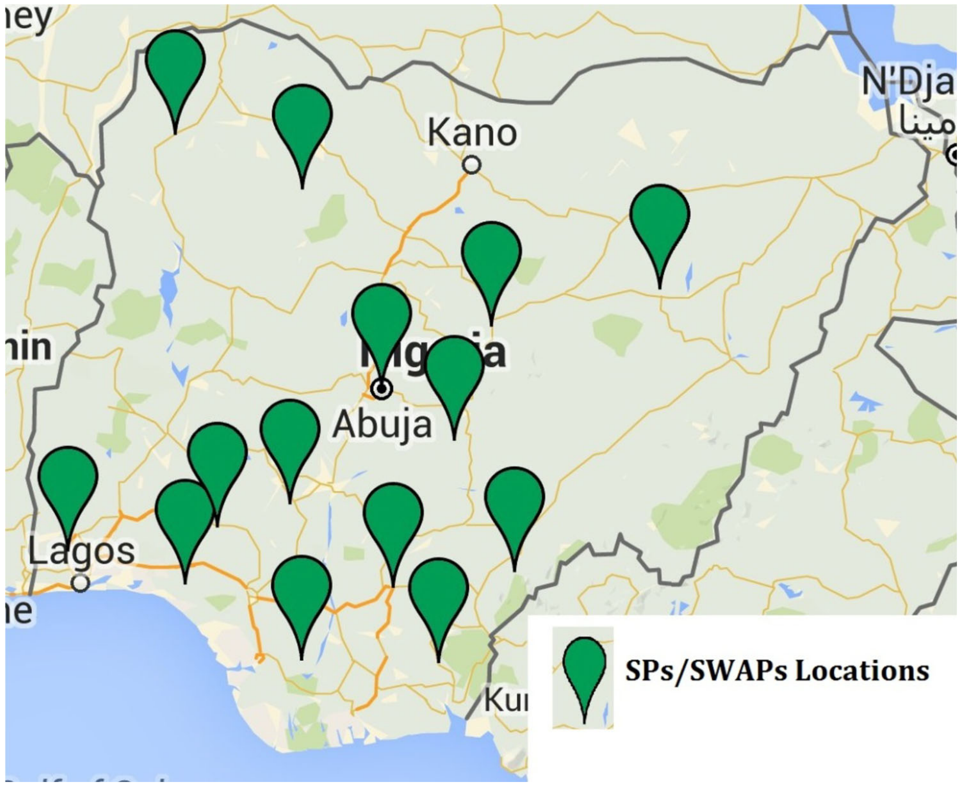

Fig. 7 Proposed locations for SPs and SWAPs for lowly populated areas in Nigeria generating coverage of 70 %

to people off-grid. Taking all the above into account in our experiment, we found five locations for SWAPs and nine for SPs. They are situated as indicated by Fig. 8.

Conclusions and further research

In this paper, we develop a hybrid approach to design a nation-wide capacitated network of solar parks (SPs) as well as solar and wind-assisted parks (SWAPs) (i.e., parks that generate both solar and wind energy) for two separate countries: Nigeria and Ghana. We take into account geographical, demographical and meteorological characteristics.

The power supply infrastructures of both countries, as well as the policies surrounding the provision of off-grid energy are analyzed in depth. In tackling the location problems occurring, we present the advantages and disadvantages of the grid method—utilized in our previous paper—and the so-called problem owner method (POM). In the POM, each potential facility location is provided by experts from the Ministry of Power, rather amply as a *sub-state* of one of the states. Therefore, in the POM approach we are forced to shift from the distance concept—used in the grid method—to a more topological vicinity concept. We choose for a hybrid approach by combining the grid and the problem owner method. We apply the grid method to regions with high population density and utilize the POM for less populated areas. Furthermore, we take into account power plants that are operational or will be so in the near future.

In the above fashion we design two separate, capacitated networks of SPs and SWAPs, one for Ghana, one for Nigeria. For Nigeria, coverage of the lowly populated areas varies from 60 % (if we place 12 facilities) to 90 % (if we place 21 facilities). To accomplish 70 % coverage for the whole of Nigeria we need: (1) 15 facilities for the lowly populated areas, of which six are SPs (so there is not enough wind), four are a mixture of SWAPs and SPs (so wind is moderate), and five are SWAPs (enough wind); (2) 47 facilities for the highly populated areas, of which 24 are SPs, and 23 are SWAPs. A mixture of SWAPs and SPs is not feasible in the latter areas. As for Ghana, we found five locations for SWAPs and nine for SPs

Thus we obtain a blueprint of a capacitated network of SPs and SWAPs that satisfies—in a sustainable way—the energy requirement of the majority of households by a facility within reasonable distance. In our research we make a number of assumptions. For instance, we assume that the population within a specific state with power plants has priority to be served before power is exported out of the state. Currently, this is generally not the case, leading to power loss due to long transmission lines. Moreover, we assume that the population per sub-state is uniformly distributed.

Fig. 8 Proposed locations for SPs and SWAPs in Ghana generating coverage of 70 %

Future research may take into account a detailed analysis of the widely branching and intricate electricity distribution system including the inherent power loss. Also, actual demographic data may be used. Another interesting issue is the cost factor, which was left out. One may think of a break-even analysis taking into account the higher costs for wind parks. All in all, we are convinced that the present study is both an enabler as well as a blueprint towards a sustainable energy future for Nigeria as well as Ghana.

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