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A GIS-based approach for electrification planning—A case study on Nigeria

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ABSTRACT

According to the latest Global Tracking Framework (2015), 18% of the global and 57% of the African population live without access to electricity services—a key impediment towards social and economic growth. Accelerating access to electricity requires, *inter alia*, strategies and programmes that effectively address and account for the geographical, infrastructural and socioeconomic characteristics of a country or region. This paper focuses on considering these characteristics by developing a Geographic Information Systems (GIS)-based methodology to inform electrification planning and strategies. The methodology is applied to Nigeria in order to identify the optimal mix of electrification options, ranging from grid extensions to mini-grid and off-grid solutions. The case study illustrates how this optimal mix is influenced by a range of parameters—including population density, existing and planned transmission networks and power plants, economic activities, tariffs for grid-based electricity, technology costs for mini-grid and off-grid systems and fuel costs for consumers. For a certain level of energy access, on-grid connections would be optimal for the majority of the new connections in Nigeria; grid extension constitutes the lowest cost option for approximately 86% of the newly electrified population in this modelling effort with 2030 as the time horizon. However, there are some remote areas with low population densities where a mini-grid or a stand-alone solution are the most economic options; deploying some combination of solar, wind, hydro and diesel technologies depending on the locational resource availability.

Introduction

The provision of reliable, secure, and affordable energy services is necessary to ensure economic and social development (IEA, 2014a). Universal access to electricity by 2030 is one of the key goals of the UN Sustainable Energy for All (SE4All) initiative (The World Bank, 2013). While the need for increased electrification rates is widely recognised in national policies in developing countries (WHO, 2009), (IEA, 2011), there are diverging views on how to achieve this. Commonly, one electrification option, such as grid extension, mini-grid or stand-alone connection, is preferred over another for various reasons depending on the perspective, the background, and the experience of the implementing body. For example, while an NGO (non-governmental organization) or IGO (international governmental organization) might have prioritised off-grid solutions, a large financing initiative such as Power Africa may lean towards expanding the transmission network (AfDB, 2014). Overall, there are limited comparative analyses that aim at providing comprehensive assessments of the optimal mix of such options (see Previous GIS-based assessments).

One reason for this lack of assessments is the general paucity of reliable energy-related information and data in developing countries and more particularly in Africa, in which this study focuses (Belward et al., 2011). Access to such information and data is, however, crucial for assessing, planning, implementing and monitoring basic services delivery. In the context of providing energy access to currently unserved populations, the use of ground level geospatial data is of key importance to help identify the most effective electrification strategy (Bazilian et al., 2012). However, such geospatial data are largely inexistent, fragmented, or inconsistent and strategic planning at the national level remains in an early stage.

This calls for strategic power planning methodologies and tools that are able to inform electrification policies despite the difficulties in accessing data. This paper presents such a methodology, drawing on Geospatial Information Systems (GIS) tools to fill such data gaps. When limited information in national databases is an issue (such as renewable energy resources, actual costs of diesel at the point of consumption, population density linked to energy demand and transmission infrastructure), remote sensing techniques are deployed to fill any data gaps (Mentis et al., 2015). The resulting analysis provides indications on where, when and what type of investments in the power sector should be made.

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The usefulness of the methodology scrutinized here for electrification expansion planning is highlighted by applying it to Nigeria and demonstrating the relevance of the insights gained for informing decision making processes. Nigeria was chosen as it is Africa's most populous country and the one with the highest deficit with regard to access to electricity (The World Bank, 2013). Nigeria also signifies great energy resource potential (EIA, 2015). It is the largest oil producer in Africa and the largest holder of proven natural gas reserves in Africa, while the wind and solar power potential are significant (OPEC, 2015). However, the country is struggling to provide its citizens with access to electricity as it has one of the lowest rates of electricity generation per capita in the world and power generation falls short of demand, resulting in load shedding, blackouts and a reliance on private generators. To illustrate, only 45% of the country's population has access to electricity (76 million out of 169 in 2012), while this figure drops to 35% in rural areas (IEA, 2014b).

The main objectives of this paper are:

- To develop a methodology to approach electrification at a national and regional level in a comprehensive and quantitative way
- To introduce a tool based on existing software that is able to come up with the optimal infrastructure and generation mix as well as cost indicators for electrification
- To apply this tool to a country and demonstrate the results in interactive and easily absorbed maps and tables

This paper starts with a description of the existing applications of GIS tools in energy and electricity planning and renewable energy assessments. The literature review serves to underline the need for a comprehensive electrification expansion methodology and tool, which is described in detail in the Methodology. That section first lists and describes the datasets needed for such a GIS-based electrification assessment. Thereafter, an electrification analysis is carried out using urban and rural energy access targets in agreement with the International Energy Agency[1]. The Results present the findings of our work thus far, whereas Conclusions and next steps present our findings regarding the practicality of the tool, its strengths as well as potential improvements.

Previous GIS-based assessments

There are a plethora of studies and projects performed recently about energy planning and renewable resource assessment, spanning from local studies (Palaiologou et al., 2011; Quinonez-Varela et al., 2007; Gormally et al., 2012), national studies (Siyal et al., 2015; Sahai, 2013) to regional studies (Sørensen and Meibom, 1999; ESMAP, 2015; Mentis et al., 2015; IRENA, 2014). Most studies, however, do not usually investigate grid extension vs. mini-grid and stand-alone solutions when it comes to electrification planning and/or focus rather on the evaluation of one particular electrification scheme.

A noteworthy exception on the continental level is introduced by Szabó et al. (2011), who investigate energy solutions in rural Africa. A spatial electricity cost model is designed to point out whether diesel generators, photovoltaic systems or grid extension are the least costly options in off-grid areas. This analysis uses a conservative estimation to delineate where grid extensions constitute the cost optimal option: set boundaries delineate the distance where a potential extension would be reasonable, i.e., 10, 30 and 50 km distance from low (LV), medium (MV) and high voltage (HV) lines, respectively. These boundaries, however, are not a result of an optimization exercise and should be further examined.

Another substantial project was undertaken by Modi et al. (2013), focusing on the National Electrification Master Plan. The purpose of this effort is to clarify the technical and investment needs for Liberia to achieve comprehensive electrification in a cost-effective way considering geospatial aspects. Network Planner, a web-based software platform, is a primary electricity planning tool used for this work. The model has been applied to Liberia, Ghana (Kemausuor et al., 2014) and Nigeria (Ohiare, 2015). However, the technical potential of renewable energy resources is not taken into account in detail and the resolution of the analysis is limited to broad administrative areas.

Kaijuka (2007) discuss the use of GIS in the planning process for rural electrification in Uganda. The aim is to identify patterns of demand and priority areas for investment. In this case, an energy benefit point system is applied to priority sectors in order to identify and design the optimal supply systems including off-grid renewable energy plants. It is concluded that rural electrification should be based on the natural resources available in each area, though the initial focus should be on hydro power due to its relative advantage over other resources in the country.

Similarly, Amador and Domínguez (2005) highlight the main problem of rural electrification, which is the selection of the most appropriate technology. GIS is used to divide the research zone into areas that are more appropriate for either conventional or renewable technologies based on techno-economic criteria (LCOE). To calculate the levelized cost of electricity (LCOE), four parameters are considered and related to costs: rural population density (inhabitants/km^2), global annual radiation, annual average wind speed (m/s) and distance of connection to the MV grid (km). This tool has been applied and verified in the municipality of Lorca in Murcia, Spain with coherent results.

Tiba et al. (2010) developed a GIS-based decision support tool for renewable energy management in rural areas. The tool permits the planning of massive insertion of renewable energy systems and the management of such systems already implanted and distributed in large spatial areas. Diverse criteria are considered in order to identify the most favourable locations for installing new energy systems. Such are the solar resource, HDI, rural electrification index, income per capita, and proximity to transmission line, existence of potable water, aptitude for diverse agricultural cultivation, wind resources and restriction of soil use.

The majority of previously developed GIS tools focused on how rural areas should be electrified and do not provide an overall electrification expansion indication for the entire country. The tool presented in this paper deals with both urban and rural areas' electrification and concludes with the least-cost split and LCOE for each location; hence, a policy/decision maker gets a first indication about the best way of electrifying Nigeria.

The aforementioned sources as well as other useful "state of the art" studies (Zeyringer et al., 2015; Kaundinya et al., 2009; Parshall et al., 2009) are used to develop a solid methodology on how to fulfill the objectives of this paper. This methodology differs from the existing studies in several ways. It develops a techno-economic tool capable of integrating the spatial dimension of energy resources, energy demand and power network, as well as cost-related indicators. Also, there are several parameters taken into account that have not been considered in the previously stated studies, for example, the technical potential of renewable energy sources, grid expansion to cover main economic activities, location of existing and planned power plants and others that are mentioned throughout the paper.

Methodology

The use of GIS tools serves multiple purposes:

- *Location based assessments*: GIS tools enable assessments to analyse energy-related geospatial information. For example, energy demand can be considered at the location where it is actually occurring. This constitutes a significant improvement over conventional national long-term modelling efforts, which lack this geographical detail (e.g., based on tools such as TIMES, MESSAGE or OSeMOSYS; Loulou

[1] KTH Division of Energy Systems Analysis collaborated with the International Energy Agency in order to contribute to the Africa Energy Outlook, 2014. Current electrification rates and electrification access targets were provided by IEA.

et al., 2005; IIASA, 1981; Howells et al., 2011). In this paper, this is applied to derive location-based projections considering the characteristics of urban vs. rural areas and their corresponding electricity access targets.

- *Remote sensing*: The use of GIS tools facilitates the integration of remote sensing techniques to derive resource availabilities and energy potentials in cases where such data are not (publicly) available. In this paper, the results from a detailed renewable energy mapping exercise performed by the Royal Institute of Technology (KTH) for the International Renewable Energy Agency (IRENA) were integrated in the analysis, considering a set of socioeconomic and geographic restrictions and technical performance of the chosen technologies (IRENA, 2014).
- *Illustration of results*: GIS is used to illustrate results at a small scale in interactive maps; this study is being done on a settlements level with a grid cell size of about 2.5 km^2. The maps are further processed to create illustrations that provide an effective science–policy interface by communicating key indicators for electrification planning “at-a-glance”, ensuring that findings can easily be absorbed by policy makers.

The methodology and the main steps followed in this study are illustrated in the subsequent simplified methodological flowchart (Fig. 1). Based on this flowchart, the GIS electrification expansion tool is programmed to derive the optimal split in a country in terms of on-grid and mini-grid and stand-alone solutions. The tool is applied to Nigeria, which has an area of 923,768 km^2 and is located between latitude 40° and 140° north and longitude 30° and 140° east.

The initial step of the analysis is the formation of the current status of the country by utilizing basic GIS data. These data sets are used as an input to an electrification model created in Visual Basic, based on cost assumptions which are described in the following section and in more detail by (Fuso Nerini et al., forthcoming). The model then provides the optimal split between on-grid and off-grid solutions. In a second step, the resulting data is further processed to investigate the types of off-grid solutions in more detail. Based on resource availabilities and potentials, the optimal split between mini-grid and stand-alone systems is obtained. Further, the corresponding LCOE is calculated. These results are being graphically represented and shown in a map as well as in tabular and chart format.

GIS data needs

As a first step, the current status of the country is described by utilizing basic GIS data, such as population density, administrative areas, current transmission network and existing power plants. This requires a review of existing geospatial datasets. The identified data for the analysis and the corresponding sources used are listed below:

➢ Administrative areas: This dataset is used to define the boundaries of the studied country (GADM, 2012).
➢ Transmission network: The existing and planned transmission network constitutes a major dataset for this analysis, as distances from the grid are a main factor in defining the optimal electrification option (AfDB, 2011).
➢ Power plants: Planned power plants have a direct impact on the expansion of the HV lines and hence affect future electrification options (AfDB, 2011).
➢ Travel time to big cities: A dataset of accessibility developed by the European Commission Joint Research Centre (JRC, 2008) is used to estimate diesel costs taking into account the transport cost. This is a key factor to calculate the potential electricity costs in mini- and off-grid solutions relying on diesel generators.
➢ Mineral reserves: Reserves may constitute a major source of income. It is expected that their exploitation will drive the electrification expansion (USGS, 2014), as the mining industry is a major energy user and requires stable energy supply.

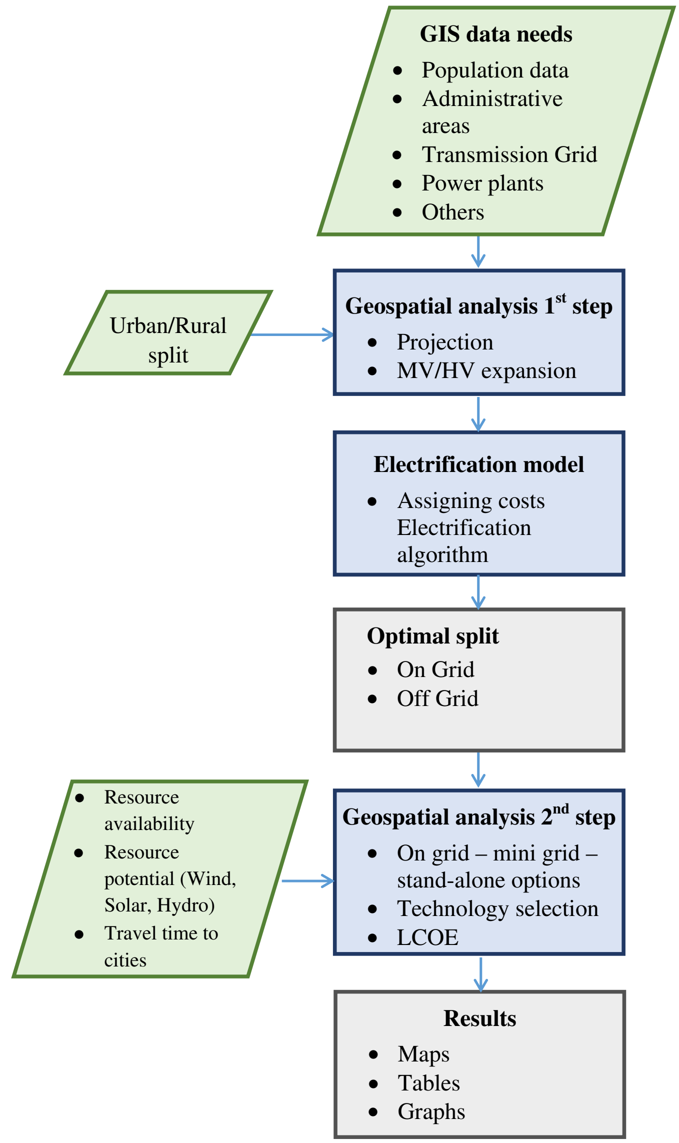

Fig. 1. Flow chart methodology.[6]

[6] Colour convention: Light green shows “data”, blue shows “process/analysis” and light gray “results/products of the assessment.”

➢ Population map: The amount of people living in a grid cell (settlements with grid size of 2.5 km) translates into the final electricity demand and is thus an important factor to identify the optimal electrification option (EUEI, 2005).
➢ Renewable energy potential map: The use of locally available renewable energy sources may provide a cost-competitive electrification option and therefore needs to be considered as part of this analysis. Solar and wind power potentials are taken into account (IRENA, 2014). For the mini hydro potential, no high-resolution geospatial data could have been identified. Instead, potentials were only available for each of the 36 states of Nigeria (UNIDO, 2013).

GIS analysis 1st step—Electricity demand forecast and planned grid expansion

Building on these datasets, projections to 2030 are made regarding population density and electricity demand. These projections are based on the current population, population growth and on whether settlements are considered urban or rural. Population growth rates were applied to the population map in order to obtain the expected population in the time frame of the analysis (2015–2030).[2]

Regarding the definitions of urban and rural areas, these differ from country to country. Hence, countries must establish their own definitions in accordance with their own needs (UNDESA, 2013). The traditional distinction between urban and rural areas within a country is based on the assumption that urban areas provide a different way of life and usually a higher standard of living than what is found in rural areas.

Energy access targets were in agreement with the International Energy Agency to be 170 kWh/capita/year for rural and 350 kWh/capita/year for urban areas. Urban areas in Nigeria are those with over 20,000 inhabitants (Anríquez and Stamoulis, 2007; Okojie, 2009).

The anticipated HV transmission lines expansion is assumed to occur based on numerous criteria:

- to comply with the African Development Bank's transmission expansion plan (AfDB, 2011)
- to connect planned power plants and those under construction (AfDB, 2011)
- to connect mines that are too far from the power grid (USGS, 2014) to be connected to the main grid with MV lines

For mines that are close enough to the existing grid, MV connections to the main grid are preferable over HV lines in terms of investment costs and electricity losses. Thus, MV lines are assumed to be used in these cases (refer to MV line length limit described in Electrification algorithm).

Further, if cost-efficient compared to mini- and stand-alone solutions, MV and LV lines are considered for connecting settlements based on factors such as distance to the grid, population data, the urban/rural split and associated cost assumptions, as further outlined in the following sections. The transmission expansion steps are presented in the following maps.

First, the administrative area of Nigeria and high-resolution population density map are shown (Fig. 2). On top of the latter map, the existing transmission HV lines and power plants are overlaid (Fig. 3).

The following map shows the existing and planned transmission HV lines as described above (Fig. 4).

Electrification model

Assigning costs

For each GIS cell, starting from the geospatial data presented above, the cost of each electrification technology is evaluated with a cost model which enables to calculate the LCOEs of the compared technologies. The obtained cost information is fed into the GIS model for the geospatial assessment to identify which of these solutions is most economical for each grid cell. The electrification options considered in the study are represented in Table 1. Those options are divided into three main categories (grid-connected, mini-grid systems and stand-alone systems). The supply technologies considered were chosen as a matrix mature technologies for electrification and depending on GIS data availability.

For the LCOE calculations, four parameters are considered and connected to costs:

a. Target level and quality of energy access: the amount of electricity that the electrified households are, or will be (in case they are not electrified), provided with, measured in kWh/household/year.
b. Population density, measured in households/km^2.
c. Local grid connection characteristics: including both the distance from the closest grid connection (km), and the national cost of grid electricity ($/kWh).
d. Local energy resources availability: in this parameter, the local resource availability is considered to evaluate the costs of the compared electrification options.

[2] Population growth rates were provided by the International Energy Agency.

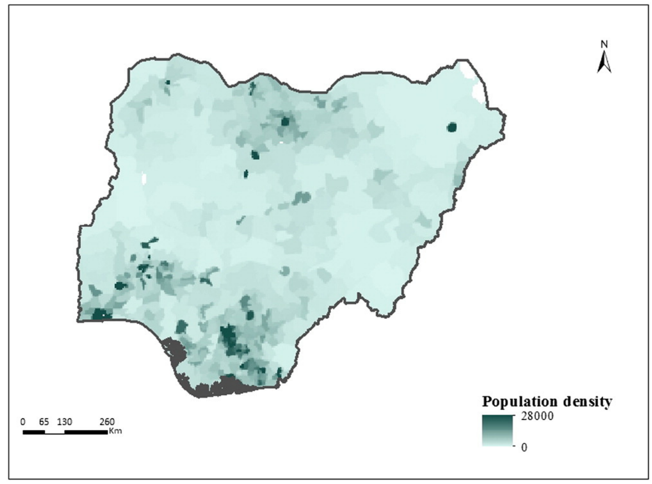

Fig. 2. Population density.

The LCOE from a specific source represents the final cost of electricity required for the overall system to break even over the project's lifetime. It is obtained with the following equation (Fuso Nerini et al., forthcoming)

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (1)$$

I_t is the investment expenditure for a specific system in year t, $O\&M_t$ are the operation and maintenance and F_t the fuel expenditures, E_t is the generated electricity, r the discount rate and n the lifetime of the system.

The LCOE calculations differ among the considered electrification options. For the mini-grid and stand-alone–based electrification options, the total system costs are considered when calculating the LCOE. On the other hand, the LCOE for the grid option is calculated by adding the average LCOE of the national grid to the marginal LCOE for transmitting and distributing electricity from the national grid to the demand location. A detailed description of the used model can be found in Fuso Nerini et al. (forthcoming).

Electrification algorithm

The GIS analysis of a specific settlement's suitability for grid connection relies on a decision algorithm written in Excel VBA (Microsoft, 2013). This procedure uses two separate, yet complementary inputs. On the one hand, it requires a *settlement table* referencing each settlement's position—i.e., its x and y coordinates—in the GIS map and its initial status in terms of electrification listed as either 1 (electrified) or 0 (non-electrified). To obtain the initial status, it is assumed that population within a certain distance from the HV grid should be equal to the electrified population of the country, i.e. 48.9% in 2015.[3] This distance is calculated in GIS applying the NEAR function using the population dataset and the HV transmission map and amounts for 9 km.

On the other, the procedure uses a *reference matrix* of standard distances to the grid along with their corresponding minimum population requirements for grid connection to be competitive. The standard distances are multiples of the 2.5 km grid cell (or settlement) width. This matrix depends on the targeted tier of electrification and is extracted

[3] This value is provided by the International Energy Agency.

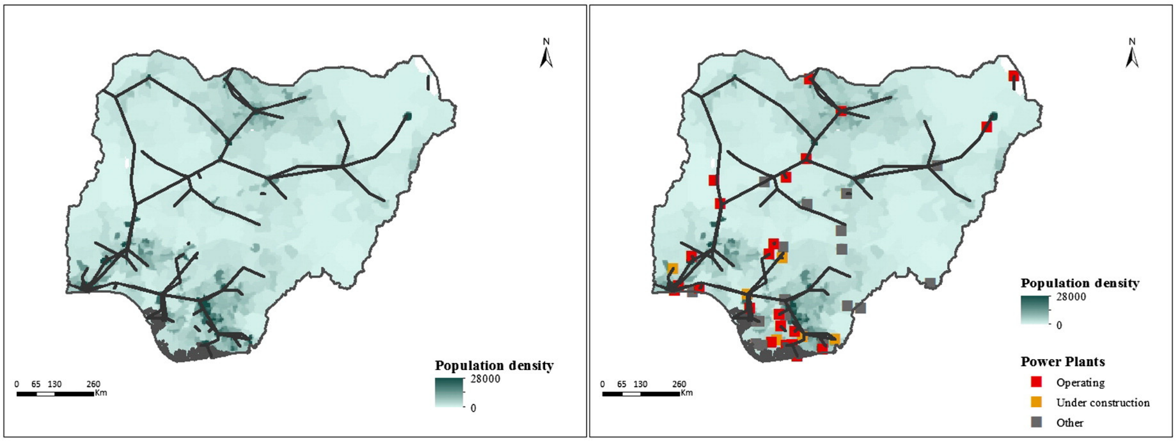

Fig. 3. Existing transmission HV lines (left) and power plants (right).[7]

[7] Other power plants are referred to planned power plants and mines that are not yet exploited.

from a comparison of the levelized cost of electricity for each electrification option (Fuso Nerini et al., forthcoming).

Based on the settlements table and the reference matrix, the algorithm evaluates if the minimum population requirement is fulfilled to justify the extension of the main grid to the settlement. For each electrified cell, iterations through all unelectrified cells are performed to test if the condition for their connection to the electrified cell are fulfilled. These conditions includes (a) having a higher number of people (and thus a higher demand) than the minimum demand required to justify a connection depending on the distance to the electrified grid cell, and (b) not causing the total additional MV grid length to exceed 50 km if it is connected.[5] If these conditions are verified, the settlement status is switched to electrified.

In parallel, the algorithm stores the length of the additional MV grid length that has been built thus far by the model to connect this new settlement. This is required to ensure that all newly electrified cells comply with the 50 km limit for MV lines. Further, this is also used to consider cost increases for each additional MV extension, due to the requirement to strengthen the previously built grid. This is achieved by linearly increasing the minimum demand (i.e., minimum population per grid cell) required to justify an MV extension with each additional electrification step.

This process is repeated with the newly electrified cells until no additional cells can be electrified, and thus until all settlements to which the grid can be economically extended are reached.

Geospatial analysis—2nd step

To calculate the levelized cost of electricity of diesel generators, the price of diesel (as given in the major cities), and the distance to cities from each grid point are considered. The calculation of the diesel costs is done in three steps as described in detail by Szabó et al. (2013). First, the transport cost is enumerated, taking into account the national diesel price, the diesel consumption of a truck, the volume of the truck and the transportation time. Then, the electricity generation cost is calculated considering the conversion efficiency of a diesel generator. Finally, the levelized cost of electricity is estimated adding labour, maintenance and amortization costs as shown in the computations below.

The following map shows the spatial variance of the electricity costs per kWh delivered by a diesel generator (Fig. 5).

Transport cost ($/kWh$_{th}$)

$$P_t = 2 * \frac{P_d * c * t}{V} * \frac{1}{LHV_d} \tag{1}$$

where P_d is the national market price of diesel ($/l), c the diesel consumption (l/h), t is the transport time (h) and V the volume of diesel transported (l) and LHV$_d$ is the lower heating value of diesel (kWh/l).

Electricity production cost ($/kWh$_{el}$)

$$P_p = \left(\frac{P_d}{LHV_d} + P_t\right)/\eta + P_{O\&M} \tag{2}$$

where η is the electrical efficiency of the diesel generator (kWh$_{el}$/kWh$_{th}$) and $P_{O\&M}$ the labour, maintenance and amortization costs.

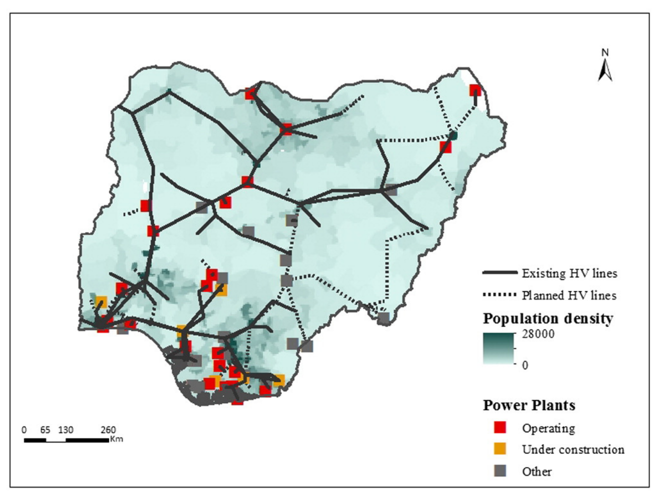

Fig. 4. Existing and planned transmission HV lines and power plants and mines.

Table 1
Technologies compared for energy access.

Category	Supply technology
Grid connection (Grid)	National grid
Mini-grid systems (MG)	Solar PV
	Wind turbines
	Diesel generators
	Mini-hydro
Stand-alone systems (SA)	Solar PV
	Diesel generators

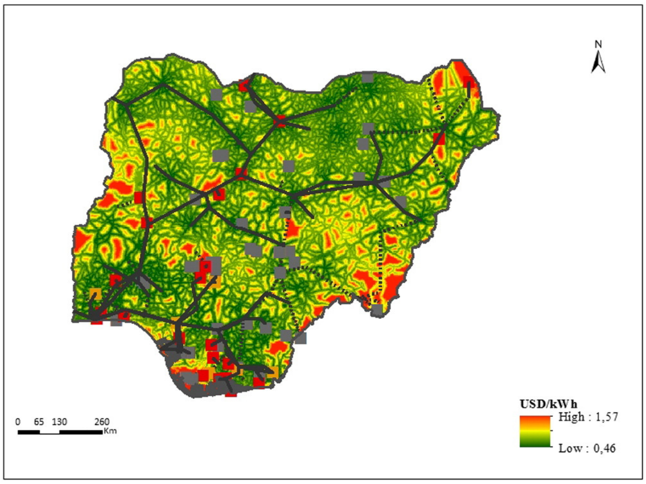

Fig. 5. Levelized cost of electricity for diesel generation.

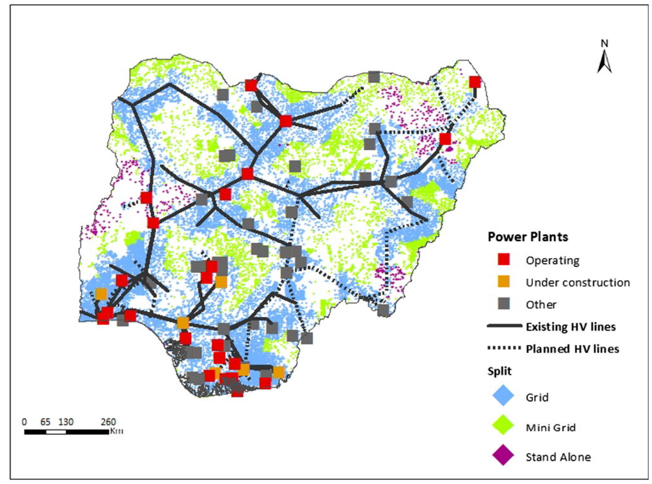

Fig. 7. Optimal electrification mix in Nigeria.

Taking into account the above, the total cost of electricity produced by diesel generators is given by the following formula:

$$P_p = \left(P_d + 2 * \frac{P_d * c * t}{V}\right) * * \frac{1}{\eta * LHV_d} + P_{O\&M} \tag{3}$$

Solar irradiation and wind power capacity factors are extracted from relevant work carried out by KTH Division of Energy Systems Analysis for the African continent (IRENA, 2014; Mentis et al., 2015) (Fig. 6). The technical potential (potential that can be realized including general socioeconomic and geographic exclusion criteria, explained in detail in IRENA (2014) and Mentis et al. (2015)) in each grid cell is translated to a cost and used as an input to the model for the mini-grid and stand-alone options based on the parametric analysis shown in the Electrification model.

The inclusion of detailed renewable energy potential maps is a significant addition of the methodology. The higher the data resolution, the more accurate the corresponding cost estimations for site-specific settlements. The outcomes of the analysis are presented in the following section.

Results

Techno-economic results

It is essential to demonstrate the outcome of this analysis in a comprehensive way. The following maps give an illustrative insight about the electrification mix in Nigeria, summarising the results of this techno-economic analysis. Based on the above, the optimal split of on-grid, mini-grid and stand-alone solutions is obtained. This is defined for certain electricity access targets and their alteration would change the results.

The analysis shows that grid-based connections are preferred for high consumption levels (depicted in blue in the following map). For 85.6% of the newly electrified population, a connection to the grid constitutes the lowest cost option. Further, there is a high geospatial diversity in technology and cost deployments. This implies a mix of grid connected as well as local generation capacity to address electrification needs most efficiently. A total of 14.3 % of the population should be electrified by mini-grid solutions (depicted in green) and just about 0.3 % by stand-alone systems (depicted in purple). It should be stated that electrification efforts will differ depending on the extent of the HV and MV grid expansion into the future.

Fig. 7 shows the potential cost, in terms of LCOE, of providing electricity in different regions of Nigeria. This includes considerations related to diesel costs based on distance from distribution stations, grid costs as a function of distance from grid, connection points and grid strengthening costs, geospatial solar irradiation, geospatial wind regimes and mini-hydro potential. The figure shows that the LCOE for areas covered by the grid is lower as compared to areas covered by mini-grid and stand-alone solutions. The LCOE ranges from 0.15 US$/kWh for areas already connected to the national grid to 1.4 US$/kWh for remote areas with low population density electrified by stand-alone diesel generators.

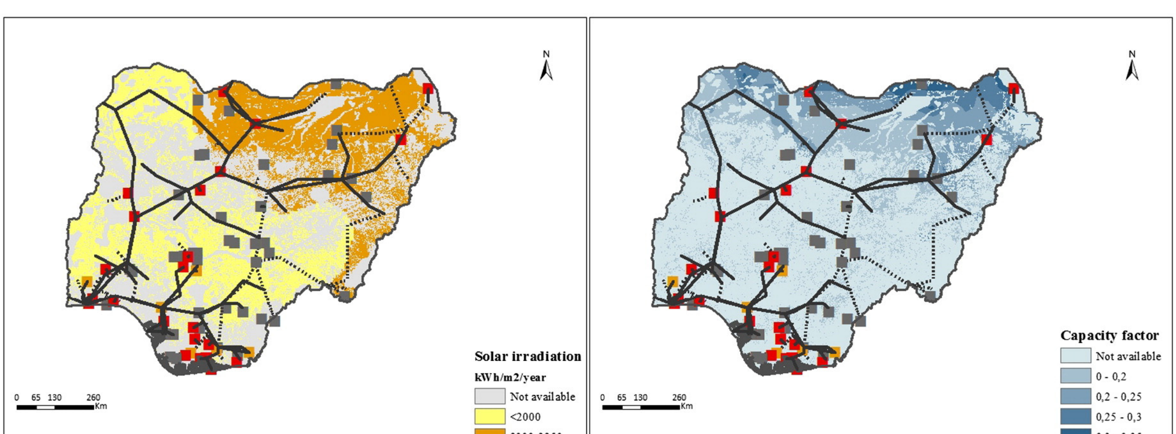

Fig. 6. Solar irradiation (left) and wind power capacity factor (right).

Table 2
Optimal electrification mix for rural and urban access targets 170 and 350 kWh/capita/year, respectively.

Item	Related physical unit	Unit
Grid distribution	1,549	Settlements
Grid distribution	33,727,783	Households
Grid distribution	168,638,916	People
Planned grid expansion (transmission with HV lines)	4,334	km
Grid extensions for those gaining access (transmission with MV lines)	78,295	km
Grid extensions for those gaining access (distribution with MV and LV lines)	1,084,544	km
Mini-grids distribution	5,475	Settlements
Mini-grids distribution	2,433,871	Households
Mini-grids distribution	12,169,354	People
Mini-grids power generation capacity	0.9	GW
Mini-grids power generation	2.1	TWh
Stand-alone systems	539	Settlements
Stand-alone systems	51,636	Households
Stand-alone systems	258,180	People
Stand-alone systems power generation capacity	0.015	GW
Stand-alone systems power generation	0.044	TWh

Complementary to the graphs, the exact results are summarised in Table 2.

Results regarding the grid expansion and the optimal electrification mix are directly derived from the geospatial analysis. The total length of the planned HV lines reaches 4334 km in accordance to national plans and to cover mining activities; whereas based on this analysis, 78,300 km of MW transmission and 1,084,500 km of distribution lines are required to provide universal electricity access.

The power generation capacity for mini-grid and stand-alone solutions is calculated externally based on the electricity access rates.

Likewise, the investment needs for grid expansion and power generation are calculated and presented in Table 3. The total cost of household electrification (100% electrification rate) and HV expansion to minerals totals US$ 15. 4 billion: US$ 11.4 billion are required for grid electrification, US$ 3.9 billion for mini-grid electrification and US$ 0.06 billion for stand-alone solutions.

The mini-grid and stand-alone technologies split are depicted in Table 4. Diesel generators and solar photovoltaics provide the largest shares of electricity for off-grid solutions. Solar technologies are key to setting up a large number of off-grid systems at small amounts of electricity consumption. At higher levels of electricity consumption, there is a tendency to rely more on mini-grids powered by diesel generators and, where available, small hydropower.

Sensitivity analysis

Fuso Nerini et al. (forthcoming) found that with increasing energy access targets least cost solutions move from stand-alone to mini-grid

Table 3
Investment needs for access to electricity.[a]

Item	Costs (billion US dollars 2013)	Unit
Planned grid expansion (transmission with HV lines)	0.571	Billion US$
Grid extensions for those gaining access (transmission with MV lines)	0.705	Billion US$
Grid extensions for those gaining access (distribution with MV and LV lines)	10.081	Billion US$
Mini-grids power generation capacity	3.946	Billion US$
Stand-alone systems power generation capacity	0.062	Billion US$
Total household electrification cost	15.365	Billion US$

[a] Investment needs for power plants in Nigeria are stated in the African Energy Outlook 2014 (IEA, 2014c). They reached 52.9 billion USD for the period 2014–2030 according to the IEA New Policies Scenario.

Table 4
Population split—off-grid solutions.

Off-grid options	Diesel	PV	Wind	Small hydro
Mini-grid	55.7%	33.4%	0.02%	10.9%
Stand-alone	56.6%	43.4%	–	–

and grid-based options. A sensitivity analysis is also carried out to highlight this change, as well as to assess how various rural electricity access targets influence the optimal split by varying the initial value of 170 kWh/capita/year. The urban access target was kept constant in order to capture the rural electricity access dynamics. It can be deduced from Table 5 that lowering the rural electricity demand from 170 to 150 kWh results in a shift from grid and mini-grid options to stand-alone solutions, while an increase in rural electricity demand to 190 kWh would result in higher grid compatible coverage.

Discussion

A number of important dynamics have emerged from the application of the methodology. Stand-alone solar can play a key role in providing basic energy access to a fair amount of the population cost-effectively (ca. 110,000 people). Moreover, as demand increases, stand-alone solar loses its attractiveness and mini- and grid solutions become more favourable. Stand-alone drops from 1% of the population to 0.1% when demand increases from 150 to 190 kWh/capita/year in rural areas. Diesel prices play a key role in determining their deployment. For non-remote, dense settlements and high demand, grid connections remain the preferable option.

However, there are certain limitations of this analysis, which are noteworthy. The analysis does not strive to replace engineering load-flow analysis, which is necessary to implement a grid expansion (Powell, 2004). Further, it is assumed that investments would be made overnight. This would imply that there are available funds and human capacities to do so. Grid expansions are commonly state-driven and are known to involve a time-consuming process. Such a process would leave many without electricity for a long period of time. Therefore, the important role of off-grid solutions to speed up electrification efforts in remote areas (until their potential later connection to the main grid) (Welsch et al., 2013) is not assessed within this paper, which relies purely on cost comparisons between the various electrification options. Furthermore, as explained in GIS data needs, the mini-hydro potential is not mapped in a detailed way as solar and wind power.

Nonetheless, the approach presented in this paper is useful since it provides insights into which areas should in any case be connected by stand-alone or mini-grid solutions. In settlements which should be connected to the main grid based on this analysis, grid expansion planning is required to understand if and when such a connection is intended, and if mini- and off-grid solutions may be preferable to ramp-up electrification efforts.

Conclusions and next steps

The methodology developed in this paper constitutes a first attempt in optimising various electrification efforts in developing countries at a national and regional level. A set of tools (GIS and Visual Basic) is introduced in order to determine the cost optimal synthesis of electrification options. These tools enable the consideration of a set of energy options, including solar, wind, hydro power, diesel and grid connections. The presented approach is complementary to already existing energy planning models, which do not consider the geospatial characteristics of energy resources, but may, for example, help to determine the optimised electricity generation costs of the future national and regional grids.

Table 5
Sensitivity analysis results—newly electrified population.

Population split/target	Rural 150–Urban 350 kWh/capita/year	Rural 170–Urban 350 kWh/capita/year	Rural 190–Urban 350 kWh/capita/year
Grid	85.49%	85.66%	85.90%
Mini-grid	13.50%	14.04%	13.97%
Stand-alone	1.01%	0.30%	0.13%

The visual representation of results supports the science–policy interface by enabling easy communication of the findings of a rather complex assessment. This facilitates an outreach to stakeholders engaged in energy planning and power infrastructure investments, such as governmental institutions, energy agencies and utilities. It will enable them to get first insights into the preferred electrification options.

Increasing Nigeria's national electricity access rate is a prerequisite to the achievement of the proposed Sustainable Development Goals (SDGs) (UNDESA, 2015). Past efforts from Nigerian policy makers have considered off-grid solutions to deal with rural electrification in the country. This study indicates the significance of integrated planning using a wide range of technology options to provide access to electricity to non-electrified population. The results of this work intend to provide policy makers and energy planners with an indication of the least cost electrification options across the country. Besides Nigeria, this methodology has been applied to Ethiopia and presented in the African Energy Outlook (IEA, 2014c).

The methodology is currently being further developed using a toolkit named the Open Source Spatial Electrification Toolkit, *OnSSET*, which will be introduced in a future publication. OnSSET will be applied in several developing countries. It aims to quantify the investment needs of increasing electrification, selecting among several technology types and taking into account the geospatial dimension of energy resources and demand. Some of the next steps in the development of the toolkit include: updated renewable potentials and population maps, detailed geospatial mini-hydro potential estimation, inclusion of additional technologies and combinations thereof (solar–diesel hybrid, wind–diesel hybrid and others), as well as considering productive uses of electricity. OnSSET will be publicly available online followed by a manual and a case study.

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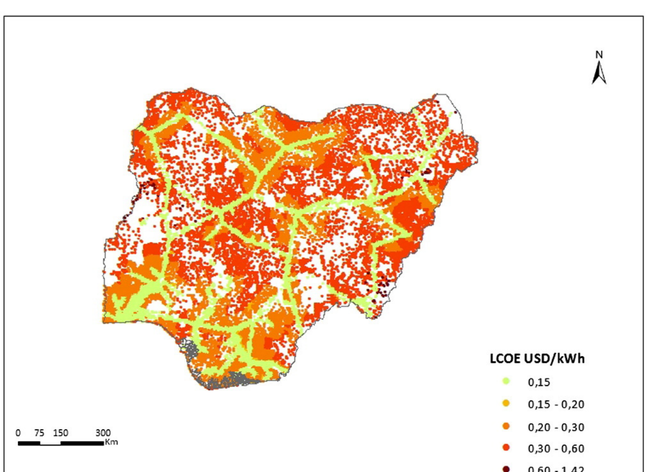

Fig. 8. Spatial levelized cost of electricity in Nigeria.

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