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Electrification planning using Network Planner tool: The case of Ghana

Francis Kemausuor [a,*,1], Edwin Adkins [b], Isaac Adu-Poku [c], Abeeku Brew-Hammond [c,2], Vijay Modi [b]

[a] Department of Agricultural Engineering, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana
[b] Columbia University, 500 West 120th St, Room 220, Mudd Building, Mail Code 4703, New York, NY 10025, USA
[c] The Energy Center, KNUST, Kumasi, Ghana

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ABSTRACT

In this study, the Network Planner, a decision support tool for exploring costs of different electrification technology options in un-electrified communities, was used to model costs and other inputs for providing electricity to 2600 un-electrified communities in Ghana within a 10-year planning period. The results show that the cost-optimized option for majority of the un-electrified communities will be grid connection, accounting for more 85% of the total un-electrified communities in each region. The total cost of electrification (which includes initial and recurring) at 100% penetration rate totalled US$ 696 million with a breakdown as follows: US$ 592 million for grid electrification, US$ 47 million for off-grid electrification and US$ 58 million for mini-grid compatible communities. Sensitivity analysis shows that model scenarios with higher electricity demand and higher household penetration rate generally recommend a larger percentage of communities for grid electrification, rather than off-grid or diesel mini-grid. One important aspect of this modelling approach is that it predicts costs for different electricity generation technologies for each of the communities involved and thus gives the planner the freedom to explore the most cost-effective technology based on existing conditions in the community and price trend of electrification inputs during the planning period.

Introduction

One of the significant drivers of socio-economic development of a country is access to electricity (Duer and Christensen, 2010; Kanagawa and Nakata, 2007). Access to electricity contributes to improvements in health delivery, education, environmental sustainability and agricultural development including crop irrigation, agro-processing and preservation of farm produce (Haanyika, 2008; Sokona et al., 2012). Despite this enormous importance, about a quarter of the world's population live without access to electricity. The worst trends in access to electricity are found in sub-Saharan African and South East Asia (Pachauri et al., 2012). Projections by the International Energy Agency (2011) indicate that by 2030, about 49% of the people in sub-Saharan Africa would not have access to electricity. In spite of the electricity access challenges in sub-Saharan Africa, Ghana has made a remarkable progress in its own electricity access rate.

Generally, increasing access to electricity has proven difficult and expensive in sub-Saharan Africa, where population is projected to be growing at a faster rate (Mulder and Tembe, 2008). Due to high the cost of investment into electricity infrastructure, policy makers and planners need tools to develop strategies for lowering the electrification cost in order to meet the economic demand of the region (Loken, 2007). In Ghana, electricity utility agencies mostly focus on the intensification of electricity access to urban and peri-urban areas already covered with existing grid network and rural areas within reasonable distance (not more than 20 km) from the existing electricity grid network. Rural electrification is generally considered to be not cost effective due to factors such as low population density coupled with high dispersion of households, low demand and persistent poverty (Mulder and Tembe, 2008; Zomers, 2001).

Even though electricity from grid extension has proved to be the most favoured approach to rural electrification in Ghana, it may not necessarily be the best option in terms of cost. In many cases off-grid connections act more as a pre-electrification option, with the community continuing to aspire for grid connection because of fixed duration and limited supply of power from off-grid projects (TERI, 2009). Off-grid technologies therefore have a role to play in the context of rural electrification. However, it is important to analyse the factors that should influence the choice of technology so that both can complement each other without competing for the same scarce financial resources.

Generally, the choice of electricity technology in the context of rural electrification is influenced by various actors and factors – prevailing policy and implementing agencies, distributors, service companies, financing institutions and household socio-economics (Reddy and Srinivas, 2009). Even though both grid-connected and stand-alone options have their own advantages and disadvantages, the underlying principle for choice of a particular mode is adopting the least cost

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* Corresponding author. Tel.: +233 32 2060242; fax: +233 32 2063573.
E-mail addresses: kemausuor@gmail.com, fkemausuor.soe@knust.edu.gh (F. Kemausuor).

[1] http://energycenter.knust.edu.gh/pages/index.php.

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technology options and with minimum maintenance requirements as far as possible (Palit and Chaurey, 2011). The technical feasibility may depend on several factors such as terrain of that location, distance to existing grid, size of loads, and local availability of resources (both fuel and human resources) (Reddy and Srinivas, 2009). If they prove to be the most feasible, solar home systems have the potential to contribute to poverty reduction and support the achievement of some of the Millennium Development Goals (MDGs). However, this contribution can only be accomplished if the systems work reliably for a reasonable period of time (Tillmans and Schweizer-Ries, 2011).

In order to extend electricity to rural and other peri-urban communities that currently lack access to electricity, energy agencies spend substantial time to undertake studies to obtain reasonably accurate estimates of electrification cost for these communities (Mahapatra and Dasappa, 2012; Pinheiro et al., 2011). Therefore, there is the need for planners to develop tools to make rapid assessment of cost-effectiveness of grid expansion and other stand-alone technology options (solar photovoltaic, diesel mini-grid) for electrifying communities. Energy system tools and models are useful, as they depict complicated systems and perform comprehensive calculations and system analyses (Hiremath et al., 2007). The identification of transition pathways between the current situation and future targets can be aided by models and tools able to account, in an integrated manner, for energy demand, energy supply and the transformation chain (Haydt et al., 2011; Tsoutsos et al., 2009). Economically, a more sound way to meet the demand is to apply least cost planning principles (Ramana and Kumar, 2009).

A model adopted in this study, called the Network Planner, is a decision support tool for exploring costs of different electrification technology options in un-electrified communities. The web-accessible model is written in Python, and developed by a team from Modi Research Group, at the Earth Institute in Columbia University, based in New York, USA. The model combines data on electricity demands and costs with population and other socio-economic data to compute detailed demand estimates for all communities in a dataset. Then, the model computes cost projections of three electrification options and proposes the most cost-effective option for electrifying communities within a specified time horizon. This helps planners both to understand costs and time frames for electrification overall, as well as to prioritise areas where grid expansion is a cost-optimized option and where other stand-alone options are preferred. The aim of this paper therefore, is to apply this model to recommend electrification technology options for 2600 un-electrified communities in Ghana and determine the estimated cost of electrification and other inputs (such as length of medium and low voltage lines), for these communities at different penetration rates.

The model incorporates Geographical Information System (GIS) tools to perform spatial processing and analyses. Starting with geospatial and population data, along with several growth and cost parameters, the model algorithmically generates a comprehensive, cost-optimized electricity plan, including a map of the projected grid extension, communities to be served by off-grid technologies, and all related costs. Because the model can generate results at any geographical scale based on the availability of data used in the modelling process, it provides policy makers a tool for planning electrification at the national, regional or local level. The model results can be visualised on a map to show the communities with their recommended electrification technology, along with existing and proposed grid network linking the communities.

Electricity planners today face dynamic and uncertain future technology costs and performance, and therefore it make sense to include alternative scenarios for evaluating technology costs and strategies (Awerbuch, 2005). According to Haynes and Krmenec (1989), a system that is either over- or under-designed will have an effect on the investment cost of electrification. In light of this, sensitivity analysis is considered to play a vital role when it comes to electricity planning. And because the model is scenario-based it allows users to perform sensitivity analysis, helping planners to understand the effects on electrification cost of changing certain factors such as electricity demand, prices and governmental policies.

Model concept and methodology

Data requirement

The data used for modelling the un-electrified communities are grouped into five (5) categories:

(i) Geospatial data — the spatial location of the un-electrified communities and the existing grid network which are needed by the model to compute distances, and therefore costs, to connect communities with MV line;
(ii) Socio-economic data — data on interest rate, economic growth rate and elasticity of electricity demand per year which are needed in estimating the discounted cost and projecting cost in a specified time horizon;
(iii) Demographic data — initial population, population growth rate, and mean household sizes which are needed to project population and household count to the base year, and to project electricity demand at the end of the time horizon;
(iv) Electricity demand — including four facility demand types: household, productive (such as grinding mills, water pumps, welding shops), commercial (shops, market places, industries) and institutional (health, education, public lighting); and
(v) Cost data — both initial and recurring costs (such as fuel, operation and maintenance) of grid electrification and the two stand-alone technologies (diesel mini-grid and solar PV). It is noteworthy that beside these above-mentioned options, any other stand-alone technology option such as wind technology can be used. This model used the two above-mentioned stand-alone electrification options because of the availability of cost and technical data, wide geographic applicability, and the acceptability to communities.[3]

Modelling projected population and its demand data

In this model, residential electricity demand of a location is dependent on a settlement's total population, and increases over time with economic and population growth. Settlements with larger total populations (towns and cities) tend to have higher electricity demand per household than small villages. In the initial step, the user loads data into the model, including the geospatial data (latitude and longitude coordinates) of the communities and the base year population of each. The model projects each settlement's population forward to the final year of the planning time horizon by applying different population growth rates to rural and urban areas based on the user-defined urban threshold (a value of population size below which a community is deemed rural and above which is deemed urban). The model applies the population growth rate every successive year till the planning year, and includes provisions allowing for a community to begin with a rural growth rate and end up with an urban growth rate as its population passes the urban–rural threshold.

With population as the basis, the model uses mean household size and electricity demand per household to compute residential demand, with additional factors accounting for economic growth and the elasticity of electricity demand. The model computes both peak demand (in kW) data and the total electricity demand (in kWh) for each settlement at the end of the specified time horizon.

The model employs two kinds of user-defined curves to model the variation across settlements of different sizes in both the number of

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[3] A more detailed description of this process, with examples, can be found on the website http://networkplanner.modilabs.org/docs/.

non-residential electricity demand points per settlement, and the magnitude of electricity demand at both residential and non-residential demand sites. The first is the “facility count curve”, which plots the number of facilities of a given type (schools, clinics, commercial facilities) against the population of each settlement. This creates a logistic curve, which quantitatively expresses the tendency for larger settlements to have more facilities of various types (i.e., cities have more schools and clinics than villages). The second is the “logistic demand curve”, which plots the variation in electricity demand for various points or structures (households, facilities) against settlement population. This creates another logistic curve, which expresses the tendency for homes and facilities in larger settlements to have higher electricity demand than homes or facilities in villages (i.e. hospitals demand more power than rural clinics; urban homes typically use more electricity on average than homes in smaller villages). Both curves employ data from the model's starting year to create a logistic curve that can be used to predict a quantity – either number of facilities or electricity demand for a given demand point – in the final year, based upon the predicted population of a settlement. These curves are based on empirical data obtained from the relevant agencies, utilities and other sources, and thus are an important aspect of localizing the model.

Modelling cost data and selecting least-cost technology

The model requires detailed cost components of the three electrification technologies such as the cost of medium voltage (MV) lines, low voltage (LV) lines, transformers, diesel generators, diesel fuel per litre, solar panels and solar batteries, as well as recurring costs, including operation and maintenance. The model also requires interest rate per year to be used to determine the discounted costs for each technology option which will be combined with other cost components in estimating the projected cost of electrification for each technology option based on the projected electricity demands at the end of the planning time horizon.

In proposing the optimal-cost technology option for un-electrified communities, the model first computes the total costs of electrification, including all initial and recurring costs, for the three different electrification technology options based on the projected electricity demands of the communities for a specified time horizon. These three potential electrification options include: (i) Off-grid — defined as solar photovoltaic (PV) electricity for households supplemented by a diesel generator for productive use (ii) Mini-grid — defined as diesel generator power with low voltage (LV) distribution for all demands type (household, productive, social infrastructure, etc.) and (iii) Grid electrification — this electrification technology consists of two grid cost components: “internal” and “external”. The “internal” grid cost refers to the LV-lines, transformers and “drop lines” needed to connect households, commercial structures and various institutions within a community. The “external” grid cost refers to extension of MV-lines from a transformer in the community to the nearest point of the MV grid network.

Thereafter, the model compares the discounted costs of the two “stand-alone” options (off-grid and mini-grid), and selects the one with the lower cost. The discounted cost of this least-cost stand-alone option is then compared with the discounted cost of only the internal component of grid connection costs for a community. If the least cost stand-alone option is lower in cost than the internal grid cost, this indicates that grid connection is not a viable option for the community, and the model designates the least-cost stand-alone technology as the final recommended electrification option. However, if the internal grid component is less costly than the least-cost stand-alone option, then the difference in these two costs represents the budget available for the external component of the grid connection costs for such communities – namely, the MV-line to connect to the nearest grid location. By dividing this value by the cost of MV-line per metre, the model obtains a key decision metric, ‘MVmax’ for each community. The MVmax, expressed in metres, represents the maximum length of MV-line which can be installed for each community before the cost of grid extension exceeds the cost of the least-cost stand-alone option. The metric is community specific and provides a simple estimate of how far the existing MV-line network can be cost-effectively extended to reach this community. Finally, the model applies a geospatial algorithm to compare these MVmax values with the actual distances between the location of unconnected communities (identified by latitude and longitude coordinates), and identifies those sites with MVmax values that justify grid connection. Those communities that are selected, indicating that grid extension is the most cost-effective technology to electrify a community, are recommended for grid connection by the model; in other words, they are ‘grid-compatible’. Those communities beyond the MVmax values are instead recommended for electrification using the least-cost stand-alone option.

Study area

This model was applied to our study area, Ghana which is located between latitude 4° 30′ and 11° North; and longitude 1° 12′ East and 3° 15′ West. Ghana lies in the centre of the West African coast; shares borders with the three French-speaking nations of Burkina Faso to the north, Côte d'Ivoire to the west, and Togo to the east and to the south are the Gulf of Guinea and the Atlantic Ocean. The latest population census shows that the total population of Ghana in 2010 was 24,658,823 (Ghana Statistical Service, 2012). Ghana is geographically divided into ten regions: Ashanti, Brong Ahafo, Central, Eastern, Greater Accra, Northern, Upper East, Upper West, Volta and Western. Ghana covers a land area of about 238,533 km^2 with varying population densities ranging from as low as 35 persons per km^2 in the Northern region to as high as 1236 persons per km^2 in Greater Accra (See Table 1). Fig. 1 shows a political map of Ghana with her existing electricity grid network. Ghana's electricity grid network is composed of 161 kV high voltage line, 33/34 kV and 11 kV medium voltage (MV) line, and 220 V low voltage (LV) line. In addition, Ghana's power system is linked by international lines to those of Togo at 161 kV, Benin at 161 kV, and Cote d'Ivoire at 220 kV (Japan International Cooperation Agency, 2008).

Data acquisition and processing

The modelling was done on a regional basis since each region in the country has different characteristics which lead to variation in some of the inputs model parameters. In this study, the year 2010 was chosen to be the base year coupled with a time horizon of ten (10) years due to the country's electrification target of 100% access by 2020. It is noteworthy that not all the data were available and in such cases those data were estimated after consultations with the practitioners. The geospatial locations of the un-electrified communities in each region

Table 1
Regional population data and population densities.

Region	Capital	Land area (km^2)	2010 population	2010 population density (persons/km^2)
Northern	Tamale	70,384	2,479,461	35
Brong Ahafo	Sunyani	39,557	2,310,983	58
Ashanti	Kumasi	24,389	4,780,380	196
Western	Takoradi	23,921	2,376,021	99
Volta	Ho	20,570	2,118,252	103
Eastern	Koforidua	19,323	2,633,154	136
Upper West	Wa	18,476	702,110	38
Central	Cape Coast	9826	2,201,863	224
Upper East	Bolgatanga	8842	1,046,545	118
Greater Accra	Accra	3245	4,010,054	1236
Ghana	Accra	238,533	24,658,823	102

Data source: Ghana Statistical Services (2012)

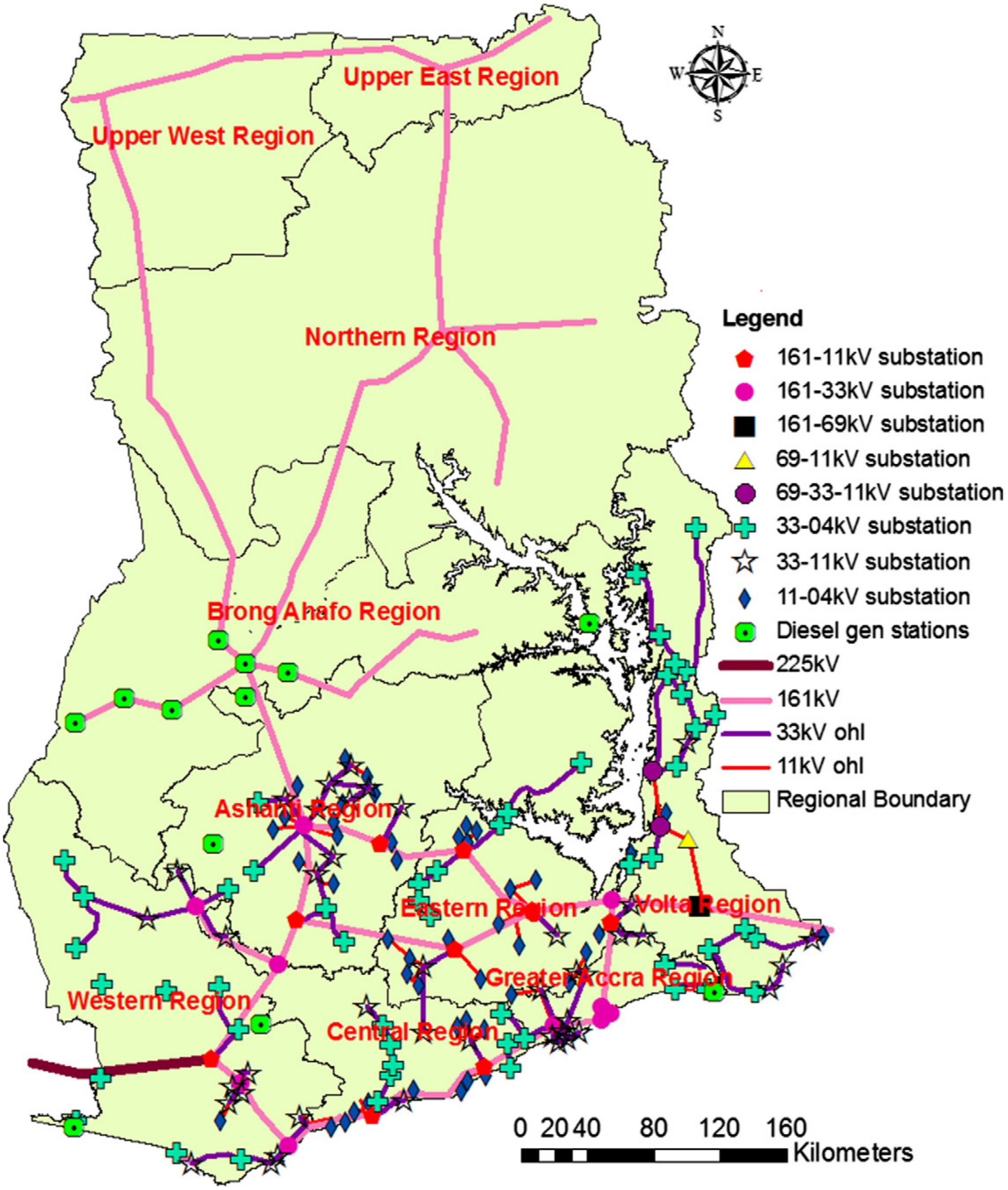

Fig. 1. Electrical network of Ghana.

that were used in the modelling for this project were obtained from the Ministry of Energy (MOE). Since detailed community population data from the 2010 census was not available at the time of the modelling, the 2000 population data of the un-electrified communities were obtained from Ghana Statistical Services (GSS) and projected to the year 2010 using population growth rate proposed by the GSS. An urban population threshold of 5000 stipulated by GSS was specified to determine whether a community is rural or urban. In addition the 2010 mean household sizes per rural and urban communities for each region were estimated from historical data obtained from the GSS. Also, solar radiation map of Ghana obtained from the Solar and Wind Energy Resource Assessment (Energy Commission, 2011) was used to estimate the peak sun hours of each region.

In modelling the demand data, the population data were classified into four categories based on population range and each range assigned an estimate average unit demand. These demand categories are used by the model to derive logistic curve functions which will be used to estimate the average unit electricity demand data of the communities based on their projected population sizes. It should be noted here that schools considered in this project include primary, junior high and senior high schools. Health posts and clinics are considered under the category of health centre. In this study, hospitals and tertiary institutions were not considered since in Ghana, these institutions are normally situated at the regional and district capitals; and are already connected to the grid. In modelling the cost data for each technology, detailed cost components of the three electrification technologies were estimated upon consultations with energy practitioners together with cost data obtained from the following energy agencies in Ghana: Energy Commission (EC), Electricity Company of Ghana (ECG) and Northern Electricity Department (NED). Market prices of medium voltage (MV) lines, low voltage (LV) lines, transformers, diesel generators, solar panels and solar batteries were used to estimate the unit cost components of each technology. In addition, the operation and maintenance costs per year were computed in consultation with energy practitioners. With regards to grid electrification, the internal cost also includes a tariff representing cost recovery of generation and transmission expenses.

One of the critical parameters needed by the model to determine the projected costs of LV-lines is the mean inter-household distance (MID) which is defined as the average distance between households in a community and this is used by the model to estimate the costs of LV line needed to connect households within a community. An average inter-household distance of 25 m was assumed (though it should be noted that this value is likely to vary throughout the country, and will be investigated for each region in a subsequent study). Moreover, the model requires interest rate per year to be used to determine the discounted costs for each technology option which will be combined with other cost components in estimating the projected cost of electrification for each technology option based on the projected electricity demands at the end of the 10-year time horizon.

During the modelling exercise, the following assumptions were considered as the base scenario: 100% penetration rate, current cost of diesel fuel per litre of US$1.02, 12 h (minimum) of operation per day of diesel generators serving communities with mini-grid systems, an average household demand of 150 kWh per year for a community with population less than 500, rural and urban population growth rates of 0.5% and 3.5%, respectively. National retail prices of solar equipment and government approved diesel prices in 2010 were used for modelling final solar and diesel mini-grid costs (see all other assumptions and data for base scenario in Appendix A). With regards to the average household demand, the model also uses a 'demand multiplier' to correlate increases in demand with increased population so that most of the communities modelled in this paper have estimated demand of more than 150 kWh. For example, a population that is classified as urban in the model, with a population of 5000, has an estimated household demand of 900 kWh or six times the base demand. During the sensitivity analysis, the effect of varying penetration rate, diesel fuel costs, mean inter-household distance and average household electricity demand were considered in alternate scenarios. For this sensitivity analysis, the Northern and Greater Accra regions were considered. What prompted the selection of the two regions was the variability in population densities of the regions, with the Northern region having the least population density and Greater Accra having the most population density as shown in Table 1.

Results and discussions

Communities analysis

The results obtained from the base scenario which represents the best estimates of parameters and assumptions used in modelling the un-electrified communities in each region are summarised in Table 2. Table 2 shows that by the end of the 10-year period, the cost-optimized option for the majority of the un-electrified communities in each region will be grid electrification, accounting for more than 85% of the total un-electrified communities in each region. This can be attributed to the extensive pre-existing grid network coverage over the country, which reduces the distances and thus the costs, to connect remaining communities. Among the two stand-alone options, in most regions a larger percentage of communities are recommended for electrification by mini-grid systems than are designated for off-grid electricity (with two regions having no off-grid compatibility at all). The two exceptions are the Northern and Upper West region. Northern region has the highest percentage of communities (20%) to be electrified by off-grid technology, followed by Upper West region (10%). The reason for these higher values can principally be attributed to the low coverage of pre-existing grid network which results in longer average distances from communities to the existing grid (i.e., high remoteness). Remote communities tend to be electrified by one of the stand-alone options. Other contributing factors to the high off-grid compatibility in the Northern and Upper West regions include smaller settlement sizes and higher solar insolation which make solar energy relatively more cost-effective.

Considering all ten (10) regions together, the total grid system cost, including capital cost plus recurring costs, as well as costs of electricity generation (which is incorporated in the model as the per kWh tariff paid to meet the electricity demands) amounted to US$592 million for the 10-year planning period. The average total cost per household for grid electrification, not only connection but also all recurring costs is US$2100. The total cost of off-grid electrification for the 10-year period amounted to US$47 million and that for mini-grid amounted to US $58 million. However, the average electrification cost per household of grid electrification per each region is 30–40% lower than the other two stand-alone options.

It should be understood that costs for grid electrification can take advantage of economies of scale: households in a grid compatible community, in effect, share the total infrastructure cost of the initial extension of the medium voltage grid line and transformer to serve the community. The result is lower costs per household when the grid is extended to larger settlements. In contrast, the cost per household of off-grid technologies does not typically scale in the same manner. Each solar system installed in an off-grid compatible community costs approximately the same as another system of similar size.

Proposed grid length and levelised cost of electrification (LCOE) analysis

Table 3 shows the required grid extension for the proposed MV and LV lines for connecting communities and the households within as well as the levelised cost of electricity provided by each electrification technology in each region. It can be observed in Table 3 that the average levelised costs of grid power (US$0.57/kWh) is lower as compared to

Table 2
Model results by region obtained from the base scenario.

Region	No. of communities	Percentage of communities with electrification technology recommendation			Cost of off-grid (US$) (10 years, initial + recurring)		Cost of mini-grid (US$) (10 years, initial + recurring)		Cost of grid (US$) (10 years, initial + recurring)	
		Off-grid	Mini-grid	Grid	Regional cost	Per HH	Regional cost	Per HH	Regional cost	Per HH
Ashanti	221	5%	15%	81%	3,120,000	3560	8,320,000	3220	49,700,000	2210
Brong Ahafo	195	4%	21%	75%	2,560,000	3560	10,300,000	3260	48,400,000	2150
Central	175	1%	3%	96%	401,000	3430	2,230,000	3100	54,500,000	1890
Eastern	247	2%	6%	92%	1,700,000	3600	3,540,000	3190	44,600,000	2120
Greater Accra	11	–	9%	91%	–	–	439,000	3020	2,420,000	1760
Northern	660	20%	10%	70%	28,500,000	3490	16,500,000	3300	102,000,000	2400
Upper East	299	1%	1%	98%	706,000	3400	939,000	3110	60,000,000	1880
Upper West	294	10%	9%	81%	7,710,000	3400	7,010,000	3230	54,000,000	2250
Volta	179	2%	2%	96%	1,840,000	3440	2,370,000	3170	80,000,000	2030
Western	319	–	6%	94%	–	–	6,000,000	3330	95,600,000	2130
National	2600	7%	8%	85%	46,537,000	3480	57,648,000	3190	591,220,000	2080

Table 3
Regional proposed length of grid extension and the levelised cost of each electrification option.

Region	Length of proposed MV lines (metres)				Length of proposed LV lines (metres)	Levelised costs (US$ per kWh)		
	Total	No. of communities	Per Community	Per HH	Total	Off-grid	Mini-grid	Grid
Ashanti	725,000	178	4070	28	557,000	1.15	1.04	0.61
Brong Ahafo	611,000	146	4190	23.2	559,000	1.15	1.05	0.5
Central	554,000	175	3170	18.6	719,000	1.12	1.01	0.51
Eastern	669,000	226	2960	29.7	520,000	1.16	1.03	0.68
Greater Accra	41,000	10	4140	27.2	34,100	–	0.97	0.56
Northern	1,586,000	464	3420	28.4	1,055,000	1.1	1.02	0.66
Upper East	648,000	292	2220	20	790,000	1.09	1.00	0.57
Upper West	780,000	238	3280	27.4	593,000	1.08	1.01	0.67
Volta	623,000	171	3640	15.3	981,000	1.11	0.99	0.38
Western	1,199,000	300	4000	25.6	1,117,000	–	1.08	0.57
National	7,436,000	2200	3510	24.3	6,925,100	1.12	1.02	0.571

the levelised costs of the two stand-alone technology options – diesel mini-grid (US$1.02/kWh) and solar off-grid (US$1.12/kWh). Here, the levelised costs of each technology in each region represent the total cost of electrification of each technology including all recurring costs for the 10-year planning duration, divided by the sum of all the electricity supplied in kWh of only those communities designated for each technology in each region. To a certain extent, the LCOE is inversely proportional to the total electricity demand. Higher demand typically justifies investment in technologies that have higher initial costs but lower recurring costs, which tends to lower per unit costs of electricity delivery over the long run. This is typically true for the electricity grid: once grid connectivity is established, it is relatively inexpensive to provide power to that line, compared with solar and mini-grid, largely due to the high recurring costs of these stand-alone options (batteries for solar, and fuel for diesel mini-grid). Stand-alone options can, however, have lower LCOE for some communities – particularly smaller communities, distant from the grid – where the high initial costs of grid extension will not prove cost-effective, even when averaged over several years. For these communities, off-grid technologies remain the least-cost option, at least for the limited time horizon (10 years) of this planning exercise. It is worth noting that, although the LCOE values are higher than typical grid tariffs (average of about US$0.12 per kWh for residential usage), this is largely due to the fact that this computation includes the assumption that all capital expenditures for the grid extension will be repaid within the 10-year time horizon of the model, which is very rapid for this long-term infrastructure.

Data in Table 3 shows that the total length of electricity-lines recommended to connect households in the regions came to 7,436,000 m of MV line and 6,926,000 m of LV line (52% and 48% respectively of the total length). This averages to 24.3 m of MV grid length per grid compatible household. The decomposition of the total length of MV and LV gridlines per each region needed in connecting communities are also shown in Table 3. It can be seen in Table 3 that the Northern region has the highest proposed MV and LV grid lines while Greater Accra has the least. This is largely due to fact that Greater Accra already had high existing grid network penetration at the start of the study period, coupled with high population density. Therefore, communities in Greater Accra are in close proximity to the existing grid network, and to each other, and thus require relatively short lengths of MV lines for connecting communities. The reverse characteristics can be attributed to the Northern region.

Cost analysis

Table 4 summarises initial costs and total costs (the latter including initial and recurring discounted costs for the 10-year period) of electrification in each region. Table 4 compares the combined cost of all the three electrification technologies, to bring electricity to every un-electrified community, under three penetration rate (PR) scenarios: the full penetration rate (100%) – defined as electrification of every household in each community – and the two other rates at 60% and 30%, defined as electrification of only 60 and 30% of households within each community respectively. To obtain the full penetration rate employing all the three electrification options, the total initial cost is estimated to be US$406 million. Comparison of the two other penetration rates reveals total initial costs of US$287 million and US $147 million for penetration rates of 60% and 30% respectively. The total cost of electrification (which includes initial and recurring) at 100% penetration rate totalled US$696 million by the end of the time horizon, which is 2020.

It can be deduced from Table 4 that the initial costs accounted to about 58% of the total discounted electrification costs at both 100% and 60% penetration rates; and to about 46% of the total discounted electrification costs at 30% penetration rate. The remaining percentages of the discounted electrification cost are recognised as the recurring costs, including operations and maintenance, as well as the cost of electricity paid by consumers.

Fig. 2 shows the patterns of total discounted cost in each region at the end of the 10-year period per each penetration rate considered. It can be revealed in Fig. 2 that the total cost of electrification at each penetration rate differs widely across regions with the total cost of electrification in Northern region (US$147 million) being the highest and that of Greater Accra (almost US$3 million) being the lowest. Costs of electrification in the five regions of Ashanti, Brong Ahafo, Eastern, Upper West and Upper East fall between US$40 million and US$80 million, whereas costs for the remaining two regions – Volta and Western – falls between US$80 million and US$120 million. Factors that contribute to the high cost of electrification in the Northern region include low existing grid network coverage coupled with a large number of relatively remote un-electrified communities. These factors are reversed for Greater Accra, which has the least total cost of electrification. These cost data mirror the technical data presented in Table 3, since the technical factors drive costs. These electrification cost ranges provide a useful guide in planning investments and financing required either from private sectors or the government to achieve Ghana's objective of universal access by 2020.

A study by the Ghana Ministry of Energy (Ministry of Energy, 2010) estimated the cost of extending electricity to the remaining un-electrified communities to US$886 million by 2020 using grid electricity only. This is about US$190 million more than the estimated US $696 million estimated in this study. But contrary to the Ministry of Energy's recommendation of grid extension to all un-electrified communities, this study recommends a mix of technologies with 7% of the communities recommended for off-grid electrification using solar home systems, 8% for mini-grid using diesel generators and the remaining 85% for grid electrification. Even though the results from the model is intended to serve as a pre-feasibility tool, the cost reduction indicates the importance of integrated planning using a wide range of technology

Table 4
Total and initial cost of all combined electrification technologies at each penetration rate.

Region	Cost of all electrification (US$) (grid, solar off-grid and diesel mini-grid)					
	Penetration rate = 100%		Penetration rate = 60%		Penetration rate = 30%	
	Total	Initial	Total	Initial	Total	Initial
Ashanti	61,100,000	36,200,000	43,4,000,000	26,000,000	27,100,000	11,500,000
Brong Ahafo	61,300,000	33,700,000	44,200,000	24,000,000	28,500,000	11,700,000
Central	57,100,000	33,500,000	41,100,000	24,700,000	25,800,000	14,700,000
Eastern	49,800,000	32,000,000	37,200,000	24,600,000	22,800,000	9,850,000
Greater Accra	2,860,000	2,020,000	2,120,000	1,240,000	1,350,000	718,000
Northern	147,000,000	85,600,000	104,000,000	53,900,000	67,200,000	26,600,000
Upper East	61,600,000	37,600,000	44,700,000	28,400,000	29,900,000	17,600,000
Upper West	68,700,000	40,600,000	48,700,000	31,000,000	30,300,000	12,600,000
Volta	84,200,000	43,600,000	57,800,000	30,700,000	37,500,000	20,100,000
Western	102,000,000	60,800,000	73,500,000	43,400,000	46,700,000	21,600,000
TOTAL	696,000,000	406,000,000	497,000,000	287,000,000	317,000,000	147,000,000

options for electrification. Notwithstanding the fact that the Network Planner uses only diesel generators for computing mini-grid costs, other mini-grid technology options such as solar mini-grid, small-hydro power mini-grid and wind mini-grids could be made available for a cluster of communities but this would need a separate analysis outside of the network planner. It is worth indicating that whereas solar costs have historically been reducing, it is expected that diesel costs would increase in the near future, in line with increases in crude oil prices. This would affect the future costs of electricity generation from these two technologies.

Sensitivity analysis

Sensitivity analysis was performed to understand the impact of changes in certain parameters on the model results. Greater Accra and the Northern region were chosen as test cases for the sensitivity analysis because they represent two extremes of population density. Greater Accra has the highest population density and the Northern region the least. The results are shown in Table 5 and the rows highlighted represent the base scenario (best estimates of parameters and assumptions, explored in detail in previous sections) while the non-highlighted rows represent scenarios run with variation in the following key parameters: Diesel fuel cost, Household (HH) demand, Mean inter-household (interHH) distance and Penetration rate. It should be noted here that, during the running of the scenarios, all other input parameters and assumptions, aside from the aforementioned parameters, are the same as the base scenario.

Effects of diesel fuel cost changes

It can be deduced from Table 5 that changes in diesel cost produce predictable changes in the prevalence and costs of the different technologies. Lowering diesel cost results in a shift in the percentage of un-electrified communities designated for off-grid or grid in the base case to be designated mini-grid compatible. In the case of the Northern

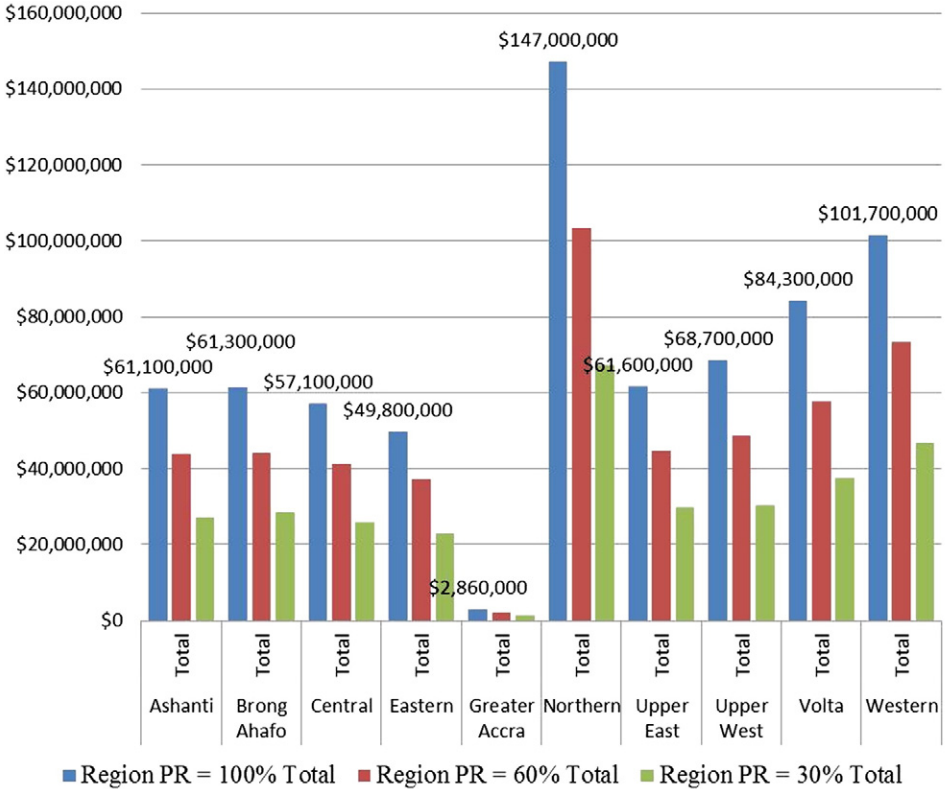

Fig. 2. Total cost of the combined electrification technologies per each region under each of the three penetration rate scenarios with the indicated cost of electrification at 100% penetration rate.

Table 5
Sensitivity analysis results obtained from the modelling.

Region	Scenarios	Percentage of communities with electrification technology recommendation			Total cost of all electrification combined (US$)	Length of proposed MV grid lines (meters)	
Northern	**Diesel fuel cost**	**Off–grid**	**Mini–grid**	**Grid**		**Total**	**Per HH**
	$0.75/ l	3%	41%	56%	135,000,000	999,000	28.5
	$1.02/ l	20%	10%	70%	147,000,000	1,590,000	37.2
	$1.50/ l	24%	–	76%	153,000,000	1,890,000	41.4
	HH demand						
	50 kWh	83.2%	0.3%	16.5%	86,500,000	92,300	9.3
	100 kWh	42%	10%	48%	120,000,000	743,000	23.8
	150 kWh	20%	10%	70%	147,000,000	1,590,000	37.2
	Mean IntHHDist						
	15 m	13%	15%	72%	141,000,000	1,690,000	38.7
	25 m	20%	10%	70%	147,000,000	1,590,000	37.2
	40 m	30%	3%	67%	157,000,000	1,440,000	35.1
	100 m	67%	–	33%	189,000,000	509,000	22.3
	Penetration rate						
	30%	35%	32%	33%	67,200,000	329,000	51.4
	60%	25%	25%	50%	104,000,000	870,000	44.3
	100%	20%	10%	70%	147,000,000	1,586,000	37.2
Gr. Accra	**Diesel fuel cost**						
	$0.75/ l	–	36%	64%	2,990,000	18,500	19.8
	$1.02/ l	–	9%	91%	2,860,000	41,400	30.1
	$1.50/ l			100%	2,750,000	50,700	33.4
	HH demand						
	50 kWh	45%	–	55%	1,890,000	5,320	6.2
	100 kWh	18%	9%	73%	2,670,000	25,700	23.0
	150 kWh	–	9%	91%	2,860,000	41,400	30.1
	Mean IntHHDist						
	15m	–	9%	91%	2,620,000	41,400	30.1
	25 m	–	9%	91%	2,860,000	41,400	30.1
	40 m	9%	9%	82%	3,370,000	31,100	25.5
	Penetration rate						
	30%	18%	27%	55%	1,070,000	11,600	44.9
	60%	–	27%	73%	2,120,000	25,700	38.2
	100%	–	9%	91%	2,860,000	41,400	30.1

region an additional 31% of the un-electrified communities shifted to be mini-grid compatible when the diesel cost was lowered from the US $1.02 per litre (base scenario) to US$0.75 per litre. Likewise, increasing diesel cost results in reduced percentage of un-electrified communities that are mini-grid compatible, shifting them to either off-grid or grid compatibility.

However, changing the cost of diesel fuel also impacts the per household and per community costs of other electrification technologies – grid and off-grid. Increasing fuel costs increases the total and average household cost of grid electrification primarily because it increases the need for MV grid lines to connect the additional communities that have shifted from mini-grid to grid compatibility. For instance at a diesel cost of US$1.50 per litre compared to the based scenario at US$1.02, the average electrification cost per household for grid extension increased from US$2400 (base scenario) to US$2500 in the case of Northern region, and from US$1760 to US$1810 in the case of Greater Accra. For the Northern region, the required proposed length of MV grid lines for connecting communities to the pre-existing grid network increases from 28.5 m to 41.4 m as the diesel fuel cost per litre is increased from US$0.75 to US$1.50. There is a smaller increase in the discounted cost of off-grid per household with increasing diesel fuel cost as well. This is a direct effect: the off-grid electrification scheme assumes that most residential power in off-grid communities is provided by solar systems. However it also assumes that the electricity for productive uses (such as high-wattage motive power) in those same communities is provided by diesel gensets, and this cost rises as diesel costs rise.

Effects of household demand changes

Changes in household electricity demand produce dramatic changes in electrification scenario outcomes. Table 5 revealed that lowering the household demand to 100 kWh from the base scenario value of 150 kWh results in a substantial shift (about 20%) in the number of un-electrified communities that were grid-compatible in the base case toward off-grid compatibility. The percentage of un-electrified communities that were mini-grid compatible remained the same. Further decrease of the household demand to 50 kWh shifted an even higher percentage of un-electrified communities from grid or mini-grid compatibility toward off-grid compatibility. The overall result of lower electricity demand is a dramatic reduction in grid compatible communities in favour of off-grid electricity. High demand communities justify higher expenditures for the infrastructure (mainly MV line and transformers) of grid extension because they will deliver larger quantities of electricity more cost effectively to customers over a longer time frame, thus repaying the initial investment. On the other hand, if demand is very small, it is less cost-effective to spend large sums on major infrastructure. Instead, small demands can be met with off-grid technologies, such as solar systems, that typically have a fairly high cost per watt, but with lower investment costs.

In the case of Greater Accra, it is realised from Table 5 that the average electrification cost per household in communities that are grid-compatible at a household demand of 50 kWh is US$1130 and increases to US$1760 when the household demand is raised to 150 kWh. It is also observed that high demands result in an increase in the number of households connected to the grid; and therefore resulting in a high projected cost of grid electrification and the associated cost per household. More so, total costs are heavily affected by the recurring costs of meeting sustained, higher level demand. The reverse is true when the household demands are lowered.

It can again be deduced from Table 5 that household demand and proposed length of MV grid lines needed to connect un-electrified communities to the existing grid network tend to rise together. This is because at a low household demand fewer communities tend to be grid-compatible and therefore require less MV grid to be connected; the reverse is true when the household demand is high. For instance, in the case of Greater Accra, 55% of communities were grid-compatible at 50 kWh but this value rises to 91% when the demand was at 150 kWh, an increase of 36%. This impacts the average length of MV line needed to connect communities. In the case of the Northern region at a household demand of 50 kWh, length of MV grid line needed to connect each community is, on average, 9.3 m per household. This is about 25% of 37.2 m, the value when the household demand is set to 150 kWh (base scenario). Likewise, in the case of Greater Accra, there is an increase in the proposed MV grid lines from 6.2 m at 50 kWh to 30.1 m at 150 kWh (base scenario), an increase of about 80%.

Effects of mean inter-household distance (MID) changes

An increase in mean inter-household distance (MID) tends to shift un-electrified communities to be off-grid compatible while lower MID shifts un-electrified communities to mini-grid and grid compatibility. It can be noted from Table 5 that increase of the MID from 25 m (base scenario) to 100 m results in no mini-grid compatible communities while lowering MID from 25 m to 15 m results in a slight increase in the percentage of communities that are mini-grid compatible. In the case of Greater Accra, the percentage of communities that are mini-grid compatible remains at 9%, as MID increases or decreases. In the case of Northern region, however, there is a gradual decrease in the percentage of communities that are mini-grid compatible as MID increases. This is because the Northern region has low population density, highly dispersed settlements, low existing grid network coverage. In this context, communities that are far away from the existing grid network (more remote) tend to become off-grid compatible when MID is increased. A different trend is visible for model results for Greater Accra, where increasing MID serves primarily to shift communities from grid compatibility to off-grid compatibility, leaving the mini-grid percentage unchanged at 9%.

Because increasing MID increases LV line length for connecting households in the communities, it thus increases cost of connection per household for both grid and mini-grid electrification technology. Meanwhile, the off-grid connection cost per household stays very nearly constant (changing only 1% for the Northern region). Moreover, as the MID increases, the number of grid-compatible communities drops significantly (see the case of the Northern region as it drops from 72% of communities at 15 m MID to 33% of communities at 100 m MID). This in turn decreases the required length of MV grid lines per household (in the Northern Region, 38.7 m of MV line per household for 15 m MID versus 22.3 m of MV line for 100 m MID).

Effects of changes in penetration rate

Scenarios with multiple penetration rates were run to address the government policy under which electricity connection targets at least 30% of households in every community in Ghana. It can be deduced from Table 5 that a penetration rate of 100% (base scenario) results in high percentage of un-electrified communities being grid compatible at a lower average connection cost per household. Reductions of the penetration rate to 60% and 30% shift a significant percentage of communities that were grid compatible to be compatible with either of the two stand-alone technologies. Lowering penetration rate tends to lower the total cost of electrification per each technology option for an entire region, however it increases the connection cost per household. This is expected, since the lower penetration rate reaches fewer households, but spreads infrastructure costs (such as MV line and transformers required to connect the community) over fewer households. For instance, in the case of Greater Accra, lowering the penetration rate from 100% to 30% reduced the number of households from 1520 to 460 and the total cost of electrification from US$2,860,000 to US $1,070,000, a reduction of about 63%. However, the electrification cost per household increased from US$3020 to US$3640.

Conclusions

Rapidly increasing Ghana's national electricity access rate is necessary for meeting the Millennium Development Goals (MDGs). The model applied in this project would assist decision makers and electricity planners to make estimates of investments needed for a range of electrification programmes given various technology options, government policies, fuel cost and other assumptions. In addition, planners can use this model to identify trends applicable to particular geographic areas, including specific un-electrified communities that may tend to be grid compatible versus those that will tend to be off-grid or mini-grid compatible within the specified time horizon. The scenarios modelled in the course of this study indicate that, by the end of the 10-year planning period (2020), a majority of un-electrified communities will be viable for grid expansion while a small percentage remain off-grid compatible. This is due to Ghana's extensive pre-existing network coverage, which at least reaches every district capital in each region.

An important aspect of this model is its potential for cost comparisons between multiple electrification technologies. When considering electrification at a national scale, the cost differential between, for example, an all-grid approach versus one that mixes grid and stand-alone technologies can amount to hundreds of millions of dollars, depending upon a country's size, population and pre-existing grid penetration. In this context, model outputs that present quantitative arguments for a variety of approaches can be instructive to policy makers, suggesting approaches for the greatest possible expansion of electricity access with limited budgets. Still, while this system provides detailed and specific scenario outputs, it is important to note that it is essential to complement these outputs with expert review, field feasibility studies, and other vetting before proceeding with electrification plans. Off-grid systems with solar photovoltaic generation can have important trade-offs. For example, even though the model recommends some communities for off-grid electrification, previous experiences in Ghana have shown that communities have often preferred grid connectivity due to the potential for use of higher-wattage appliances, and may consider solar power to be inferior, or even discontinue using off-grid systems to put political pressure on governments, particularly if the grid has been extended to neighbouring communities (Kemausuor et al., 2012). Also, utilities often find it difficult and expensive to manage and maintain isolated systems located in remote areas, due to difficult access and poor communication conditions, and complex transportation logistics (Dornan, 2011; Pinheiro et al., 2011). These drawbacks, however, must be balanced against the substantially reduced costs that off-grid systems can offer for remote users. Implementers may need to strengthen institutions and education of beneficiaries, perhaps in a manner that highlights the role of off-grid systems in providing smaller amounts of power in the short term, anticipating grid extension in the future, as demand rises.

The results from the Network Planner have shown that extending the grid to all communities may not be the most cost optimal solution to solving the rural electrification challenges in Ghana. Working with mini-grid and off-grid technologies, where they are cheaper, may yield wider financial benefits if well targeted. Off-grid and mini-grid solutions can also function as stop-gap measures until the grid can be extended to smaller, more remote communities. The extent and duration of this approach depend on national electrification plans and, in particular, the purposes of rural electrification. For example, low-wattage lighting needs in isolated rural areas can be served with off-grid solutions perhaps for several years. However, for locations where it is desired to promote agro-industries, mini-grid and grid solutions may be favourable.

In Ghana's case, costs vary less across regions than they might otherwise in large part because of the electrification model that Ghana chose in the early days: sending the grid to all regional and district capitals. This established a basic grid “backbone,” making it easier to connect communities later, once generating capacity and demand rose. This is a model that may be instructive for other countries in the sub-Saharan Africa who are beginning to expand electrification infrastructure.

In this paper, we have not discussed financing schemes for the proposed electrification options since the government of Ghana has already attracted donor funding to reach its current electricity access rate (Kemausuor et al., 2011) and we expect the lessons learnt from past experience to serve as a guide in raising further funding to complete the electrification programme. Nonetheless, we recognize that modelling tools like this can be helpful for countries with low electricity access to more easily develop pre-feasibility studies and ultimately access funding sources for electrification programmes.

It is therefore recommended that the Ministry of Energy defines a more broad-based plan that integrates mini-grid and off-grid solutions employing renewable energy. As part of the process leading to a definition of the broad-based plan, a few pilot projects could be implemented. Off-grid pilots using solar home systems could be implemented in the Northern and Upper West Regions where the percentages for communities falling into this category on a least-cost basis are as high as 20% and 10%, respectively. Mini-grid pilots based on renewables could also be implemented in the areas identified in the Ashanti and Brong Ahafo Regions with un-electrified communities where the percentages for mini-grids as the least cost option are 15% and 21%, respectively. Lessons from these pilots could be drawn to inform the broad-based plan for reaching 100% electrification by 2020.

It is further recommended that the Network Planner model is upgraded to address its current limitations. In particular, an enhanced Network Planner should be able to consider renewable energy systems like small hydro and bioenergy plants in addition to diesel generation for the mini-grid option. An enhanced Network Planner should also be able to consider other renewables in addition to solar home systems, like small wind turbines for off-grid electrification.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.esd.2013.12.009.

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