Energy 95 (2016) 255–265

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

# A cost comparison of technology approaches for improving access to electricity services

Francesco Fuso Nerini*, Oliver Broad, Dimitris Mentis, Manuel Welsch, Morgan Bazilian, Mark Howells

*KTH Royal Institute of Technology, Division of Energy System Analysis (KTH-dESA), Stockholm, Sweden*

ARTICLE INFO

*Article history:*
Received 20 February 2015
Received in revised form
17 November 2015
Accepted 29 November 2015
Available online 31 December 2015

*Keywords:*
Energy access
Least cost energy modeling
Power planning
Rural electrification

ABSTRACT

The UN's *Sustainable Energy For All* initiative has made universal access to energy by 2030 a key target. Countries wherein budgets are constrained and institutions stressed are faced with the challenge of further extending energy services – and doing so significantly. To meet this goal for the power sector in a cost-effective way, governments have to consider the deployment of a mix of stand-alone, mini-grid and grid-based solutions. To help inform analysis, planning and the decision process, this paper presents a simple, transparent, least-cost model for the electrification of rural areas. The approach builds on four key parameters, namely: (i) target level and quality of energy access, (ii) population density, (iii) local grid connection characteristics and (iv) local energy resources availability and technology cost. From an application perspective, this work can be used both for (1) fast assessments of specific energy access projects, and (2) to inform more complex regional studies using a geo-referencing software to analyze the results. Such applications are presented in the results using country case studies developed for Nigeria and Ethiopia. These show how the strategy for expanding energy access may vary significantly both between and within given regions of energy-poor countries.



## 1. Introduction

Over 1.3 billion people in the world still lack access to meaningful quantities of electricity [1]. The corresponding gap in access to modern energy services affects the socio-economic development of energy-poor countries, and acts as a brake on economic growth. Universal access to electricity by 2030 is one of the key goals of the UN Sustainable Energy for All (SE4All) initiative [2]. Additionally, Sustainable Development Goal number 7 (SDG7) is to 'ensure access to affordable, reliable, sustainable and modern energy for all' [3]. However insufficient financial resources, lack of effective planning, and fast population growth are just some of the many challenges to achieving this goal. Local utilities and governments struggle to find solutions that can provide an acceptable level of energy access to the larger proportion of their population without exceeding the limited budgets that they have to work with. A combination of energy solutions is required in order to bridge the gap in an optimal way.

In this context, the cost comparison of various technologies, including on-versus off-grid energy technologies for energy access, is significant. Such an assessment can be made on different scales ranging from local, to national, regional and continental levels. A limited and selective description of some of those studies follows.

At a local level insights are drawn from case studies that involve specific circumstances. For instance, rural electrification options have been compared with multi-criteria approaches for general rural areas [4] and for rural communities in the Brazilian Amazon [5]. A recent study assessed the energy supply and use patterns for a rural village in West Africa, presenting results focusing on the potential for the development of micro-grid and off-grid solutions [6]. Local conditions determining the cost-competitiveness of certain off-grid electrification solutions have been addressed for a rural village in Algeria [7]. Decentralized energy approaches were also compared for a 'hypothesized' village in India examining the economic sustainability of different system configurations [8]. In general, local approaches show how the solutions for one region might not be appropriate for another [9].

At a national level, recent studies compare grid and off-grid energy solutions in countries such as Liberia [10], Ghana [11] and Papua New Guinea [12], amongst others. The Energy Sector

* Corresponding author. Brinellvägen 68, 100 44 Stockholm, Sweden.
*E-mail address:* ffn@kth.se (F.F. Nerini).

http://dx.doi.org/10.1016/j.energy.2015.11.068

Management Assistance Program (ESMAP), for example, has developed several studies evaluating techno-economic characteristics of energy solutions for electrification [13] and provides national-scale models for evaluating the cost of energy technologies for low- and middle-income countries [14].

Other approaches use global models for the comparison of electrification solutions on a larger scale [15]. Various global resources have been developed in order to support a wide range of analysis. The International Renewable Energy Agency (IRENA) has developed studies and databases of resource potentials for several renewable energy technologies [16], for example.

Interestingly, much of the afore mentioned analysis develops ad hoc or context specific approaches and case studies. New tools might be developed, or an off the shelf model calibrated to a new setting. Doing so helps ensure analysis is locally appropriate. However, while technical solutions are often different, key aspects of the dynamics of their selection are similar – in particular when these relate to costs. Thus articulating a simplified general approach to indicate the cost-optimal choice of electrification technology has value. It can help strip off superfluous detail that is part of existing toolkits, while providing a 'bare metal' starting point for others. In particular it might be: rapidly calibrated to a specific setting for a coarse and direct assessment; easily adapted and adopted into a broader array of analysis; or used as the starting point for the development of new, or more nuanced approaches. It therefore needs to be as simple as necessary, transparent, and easily accessible. We identify four key parameters:

a. Target level and quality of energy access
b. Population density
c. Local grid connection characteristics
d. Local energy resources availability and technology cost

These parameters and their effect on the choice of electrification technology will be defined. The parameters are used to calibrate a straightforward formulation in a spreadsheet using standard parameter ranges and technology data that can easily be tailored to a specific locality (Country, State, etc.). For consistency, the research is directly related to the World Bank SE4All electricity access metrics, which are likely to be key metrics for SE4All and SDG7 in the medium term. Finally, the adoptability of the approach can inform broader efforts. For example, its use in a geo-referenced framework formed an essential component of GIS-based assessments of Nigeria and Ethiopia as a contribution to the International Energy Agency World Energy Outlook 2014 [17].

## 2. Methodology

A cost comparison between selected grid, mini-grid and stand-alone energy technologies available for energy access – presented in Table 1 – was conducted by varying the values of key techno-economic parameters within representative ranges.

**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 |
| | Biogas generators |
| Stand alone systems (SA) | Solar PV |
| | Diesel generators |

The cost model was built to represent the energy system in a simplified way. As such, two cost metrics were used to compare technology options and evaluate the effect of selected key parameters. These are the Levelised Cost of Electricity (LCOE), and total cost per household connected between 2015 and 2030. The LCOE for a specific energy source represents the final cost of electricity required for the overall system to breakeven over the project lifetime. The LCOE is given by Equation (1):

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

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

The total cost per household was calculated for the timeframe 2015–2030. It is the total cost of giving a single household access to energy in a given context – i.e. for a given set of parameter values – over the model time period. The total cost per household can be calculated using Equation (2).

$$Total\ cost\ per\ household_{2015-2030} = \frac{\sum_{t=1}^{n} \frac{I_t + O\&M_t + F_t - S_t}{(1+r)^t}}{hh} \tag{2}$$

where, $S_t$ is the salvage cost of elements being dismissed in year $t$ and $hh$ is the number of households served by the energy system in question: $hh$ is equal to 1 for stand-alone solutions, and to the settlement size (number of households) for grid and mini-grid based solutions. Transmission and distribution needs for grid and mini grid technologies are determined based on a methodology using a simple tree-like structure to assess the length of power lines required to reach a settlement [15]. The specific costs and technology assumptions used in this analysis are reported in Annex A.

The LCOE and the Total cost per household from 2015 to 2030 were calculated for all selected technologies, across all parameter combinations as summarized in Table 2. This mapping confirmed important system dynamics involved in the selection of electrification options for rural areas.

The following paragraphs contain detailed presentations of both the cost parameters and the subsequent metrics used to quantify them.

### 2.1. Level and quality of energy access

The fact that the quantity and diversity of services to be provided using electricity influences the choice of the energy solution has been proven in a number of studies [18]. Other literature discusses the nebula of different metrics that exist to measure energy access [19]. Although there is no universally agreed-upon definition of energy access [2], this research adopts the multi-tier categorization of household Energy Access proposed by the World Bank's Global Tracking Framework for SE4ALL. This metric was chosen in order to help support a number of ongoing efforts promoting its use within the Sustainable Energy For All programme. Further, this structure has been officially adopted within all related WB projects and an increasing amount of relevant national data is (and will be) made available following this format. This represents a relevant advantage considering data paucity issues that usually affect energy access studies [20].

Operationally, this metric relates a level of household appliance use to a specific tier of energy access as defined in Table 3. From the appliances that characterize a specific tier, an average electricity

**Table 2**
Parameters varied in the study.

| Parameters | Metric | Value range |
|---|---|---|
| Target level of energy access | Multi-tier categorization of energy access | Tier 1–Tier 5 |
| Population density | Households/km$^2$ | 50–650 households/km$^2$ |
| Local grid connection characteristics | Distance from closest grid connection post (km) | 5–50 km |
| | National cost of grid electricity ($/kWh) | 0.05–0.4 $/kWh |
| Local energy resource availability and technology cost | Solar Irradiation: kWh/m$^2$/year | 1500–2500 kWh/m$^2$/year |
| | Wind: capacity factor | 0.2–0.4 |
| | Mini Hydro: Availability in the vicinity | Available/unavailable within a 10 km radius around the settlement |
| | Biogas generators: Availability of biomass feedstock (such as large-scale livestock farms) in the vicinity | Available/unavailable within a 10 km radius around the settlement |
| | Diesel: US$/l | 0.5–1 US$/l for mini-grid applications<br>1–2 US$/l for stand-alone applications |
| | Capital cost of generation technologies | Varied by 20% of the baseline cost |

**Table 3**
Tracking electricity access with a Multi-Tier framework[a].

| Level of access | Tier-0 | Tier-1 | Tier-2 | Tier-3 | Tier-4 | Tier-5 |
|---|---|---|---|---|---|---|
| *Indicative appliances powered* | *Torch and Radio* | *Task lighting + Phone charging or Radio* | *General lighting + Air circulation + Television; Computing; printing* | *Tier 2 + Small appliances (i.e. General food processing and Washing Machine)* | *Tier 3 + Medium or continuous appliances (i.e. Water heating; Ironing; Water Pumping; Rice cooking, Refrigeration; Microwave)* | *Tier 4 + Heavy or continuous appliances (i.e. Air Conditioning)* |
| *Consumption (kWh) per household per year (recommended from the WB framework)* | *<3* | *3–66* | *67–321* | *322–1,318* | *1,319 –2,121* | *>2,121* |
| *Consumption (kWh) per household per year – As calculated in* [18] | - | *22* | *224* | *695* | *1800* | *2195* |

[A] For this study a simplified version of the multi-tier framework for household energy is used with a focus on the access to household electricity services. A complete description of the framework can be fund in [28].
Source: World Bank Global Tracking Framework, Source: Elaboration of the authors from Ref. [2].

demand per household is calculated. This study considers levels of electricity access from tiers 1 to 5.

### *2.2. Population density*

Population density is a key parameter for choosing electrification technologies. When transmission and distribution (T&D) of electricity is required, low population densities result in higher costs per connected household and increased distribution losses due to the longer T&D distances. These considerations are included by varying population density from lower (<50 hh/km$^2$) to higher values (>650 hh/km$^2$)[1] by incremental steps of 25 hh/km$^2$.

### *2.3. Distance from closest grid connection point & national unit electricity cost*

The distance from the group of houses to the nearest grid connection point influences the cost of electricity transmission for two reasons: intuitively, longer transmission lines result in both higher capital cost expenditures for grid connection and in higher energy losses for a given settlement connection. This results in higher per capita energy costs relating either to the need of purchasing larger electricity volumes from the national grid, or to increased capital costs for transmission systems with lower electricity losses.

In parallel, higher costs of electricity from the national grid increase the total cost of grid based solutions over the considered timeframe. In countries with higher electricity production costs, mini grid and stand-alone solutions can therefore result in more cost competitive service provision alternatives.

To take this into account, the distance to the grid connection point was increased from 5 to 50 km$^2$ while the cost of grid electricity was increased from 0.05 to a maximum of 0.25 $/kWh.[2]

### *2.4. Local energy resource availability and technology cost*

The level of energy resources in the area where the electricity is needed is an important parameter for choosing the least cost energy solution. This study considers energy resource ranges typically encountered in energy access projects:

[1] For simplicity, and because the energy demand calculations are related to the number of households in the WB Global Tracking Framework, population density is measured in number of households/km$^2$ for this study.

[2] 50 km is assumed to be the longest technically viable distance that can be covered using medium voltage lines [12].

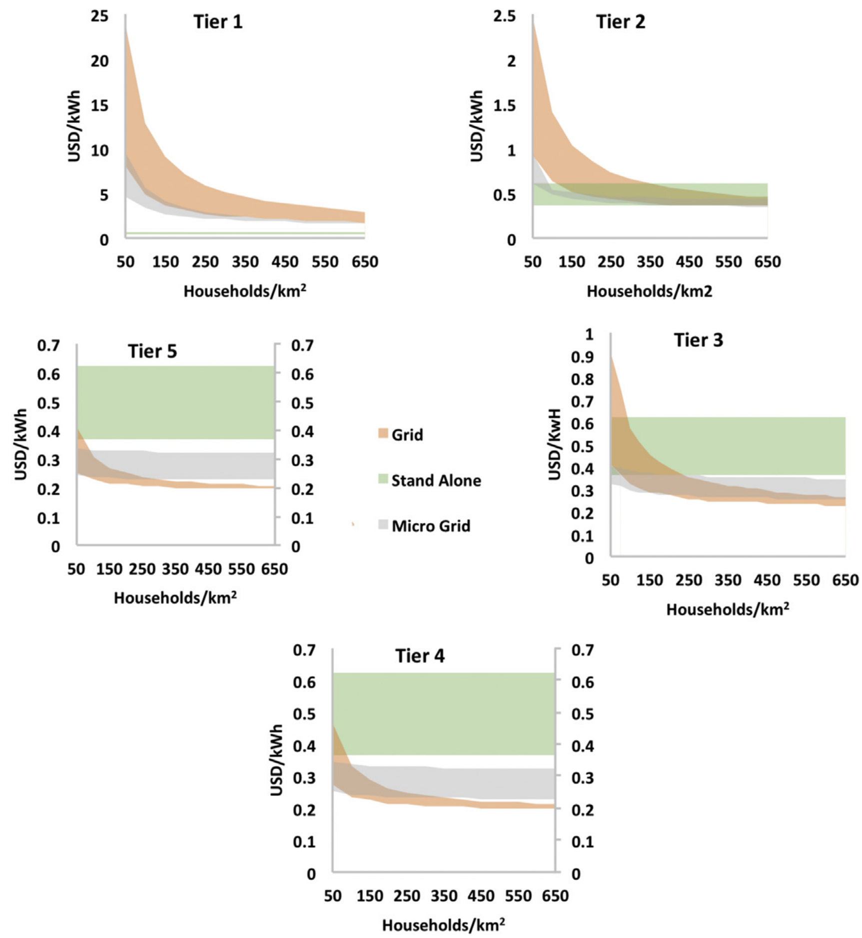


**Fig. 1.** LCOEs of providing energy access with grid, mini-grid and stand-alone technologies.[3]

- Solar Irradiation potential was assumed to be either high (2000–2500 kWh/m$^2$/year) or medium (1500–2000 kWh/m$^2$/year) [21].
- Wind Capacity Factor (CF) values span from 0.2 to 0.4 [21].
- Mini Hydro: is either available or not within 10 km from the demand center
- Biomass feedstock for biogas production: is either available or not within 10 km from the demand center
- Diesel: the cost of fuel depends on the geographical location. First, different countries have different diesel cost prices. For instance, 2012 diesel pump price variability across Africa includes lows of 0.1 US$/l (Libya, subsidised cost) and highs of almost 2 US$/l (Malawi and South Sudan) with a continental average of 1.18 US$/l [22]. Second, the cost of diesel in a given country can increase depending on the distance to the closest supply point [23]. To address this variability the cost of diesel was assumed to be between 0.5 and 1 US$/l or 1 and 2 US$/l for diesel based mini-grid and stand-alone solutions respectively.

Finally, capital cost variations for generation technologies – relating either to regional cost specificities or to differences in learning-curve based cost improvements – affect the least-cost system configuration. This is accounted for by reducing the capital cost of generation technologies by 20%. This helped evaluate how lower investment costs affect the competitiveness of each electrification solution.

## 3. Results

The results are presented both in terms of LCOE and of total cost of energy access per household from 2015 to 2030. We first present general comparative results of on-versus off-grid energy technologies before focusing on single parameter analyses of the key parameters described in paragraph 2.

Reporting the LCOEs of providing energy access with selected technology types, Fig. 1 shows that the least cost solutions move from predominantly stand-alone systems over to mini-grid and grid connected solutions with both increasing target energy access level, and increasing population densities. Specifically, settlements with low energy requirements and low population densities rely exclusively on stand-alone solutions. As we move to higher energy tiers, high fixed costs of grid and mini-grid based systems are absorbed by larger energy volumes and bring the LCOE down. Similarly, larger energy requirements of areas with higher population densities bring the unit cost of energy down for systems with high upfront investments. This remains true in cases with low electrification targets.

[3] Technologies included:1) GRID: Grid connection in between 5 and 20 km of distance, with a national grid electricity price of 0.15 USD/kWh. 2) MINI-GRID: Diesel MG with a Diesel price of 0.5 US$/l, Wind energy based MG with Cf = 0.2, PV based MG with Irradiation between values of 1500–2500 kWh/m$^2$/year. 3) STAND-ALONE: Diesel based SA solutions with Diesel prices between 1 & 1.5 US$/l, PV based SA solutions with Irradiation values between 1500 and 2500 kWh/m$^2$/year.

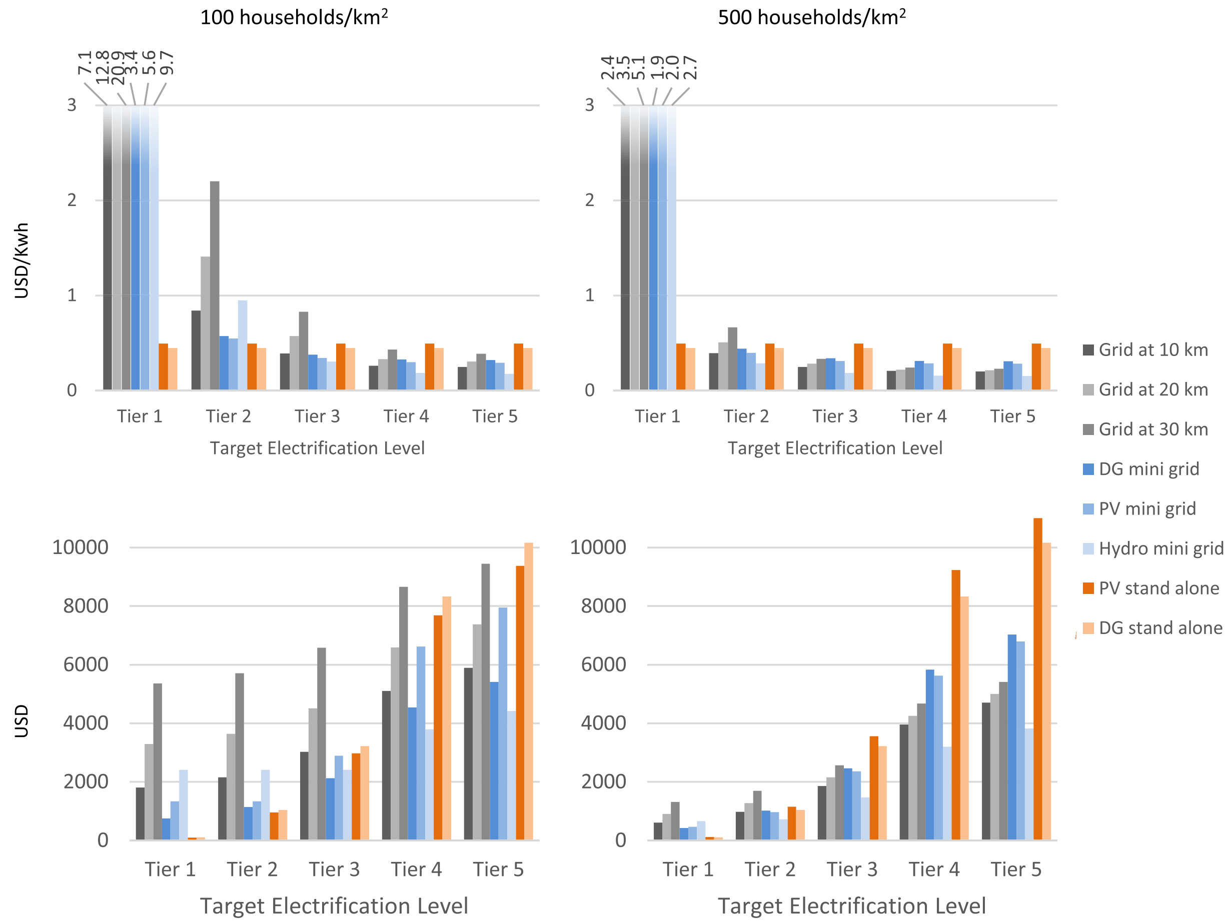


**Fig. 2.** LCOEs and total costs over the model period for reaching different levels of energy access.[4]

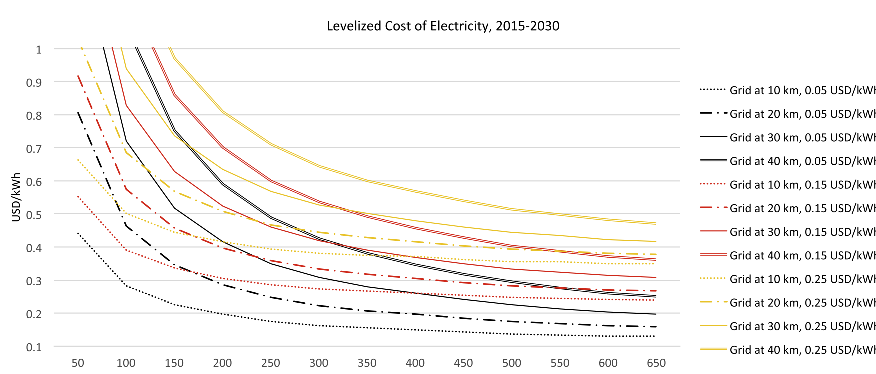


**Fig. 3.** LCOEs and total costs of energy access per household under different grid connection characteristics, Tier 3 of electricity access (For each distance the LCOE is calculated using three different unit costs of electricity).

The next few paragraphs focus on how each of the considered parameters influence the choice of solutions for energy access.

### 3.1. *Target level of energy access*

The graphics in Fig. 1, from Tier 1 round to Tier 5, show how the target level of energy access influences the choice of the least cost energy solution. When aiming at the lowest access level, Tier 1, stand-alone energy solutions are far cheaper than solutions that require transmission and distribution of electricity: the low amount of energy required by each household does not justify the capital investment for transmission and distribution systems. Stand-alone solutions are therefore the least cost solution for all Tier 1 situations regardless of population density.

Moving to a Tier 2 of energy access, stand-alone solutions loose some of their advantage but remain interesting for low population densities. With increasing population densities solutions with transmission and distribution needs become more cost

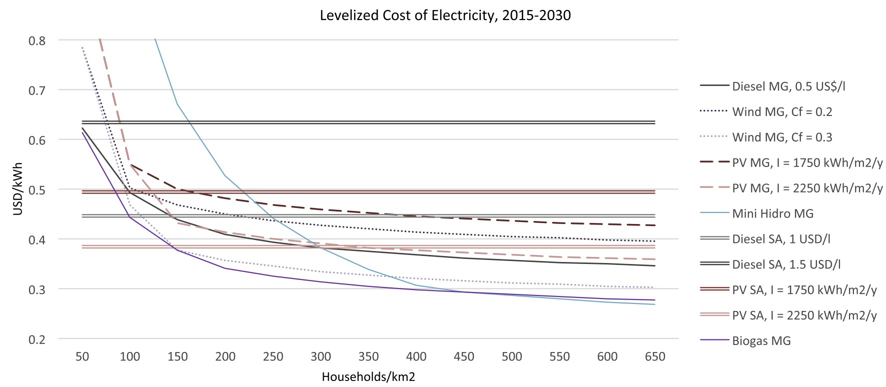


**Fig. 4.** Cost comparison of selected stand-alone and mini-grid technologies with Tier 2 of energy access target.

competitive. In particular, mini-grid solutions become competitive at relatively low population densities of 100 households/km$^2$, depending on local conditions.

At higher tiers of energy access, stand-alone solutions are more expensive than other solutions, both per kWh and in terms of total cost per connected household. Higher energy requirements make the investment needs for transmission and distribution more economic on a cost per kilowatt basis.

Fig. 2 focuses on the cost dynamics of selected energy systems when moving across tiers of energy access with population densities of 100 and 500 households/km$^2$. In terms of LCOE, providing energy access using grid and mini-grid solutions for a Tier 1 situation can cost in excess of 10 USD/kWh. On the other hand, selected stand-alone solutions have LCOEs ranging from 0.4 to 0.5 USD/kWh. Correspondingly, stand-alone systems are the least cost option for Tier 2 situations only in cases of low population density as grid-based systems become more competitive, thus conceding solution space to grid-based solutions at higher population densities. Stand-alone solutions continue to loose in cost competitivity across higher energy access targets. For the two population densities presented in Fig. 2 most mini-grid and grid solutions already have LCOEs below 0.4 USD/kWh for Tier 4. The total cost per connected household also varies significantly from one electrification target to another. For achieving a Tier 1 of energy access with stand-alone solutions the cost over the considered period can be as low as 100 USD/Household. Achieving a Tier 2 energy access with stand-alone and mini-grid solutions can cost 10 times as much. These costs continue to rise considerably with higher tiers of energy access. For instance, the cost of achieving a Tier 5 can be 50 to 100 times larger for a Tier 1, depending on local energy sources.

### 3.2. Population density

Settlement size, and therefore population density, influences the cost of adopting energy solutions with transmission and distribution requirements. Higher population densities provide a higher population basis to share the T&D costs. As a result, grid and mini-grid based solutions become more cost competitive than stand-alone solutions with increasing population densities. These dynamics are shown both in Figs. 1 and 2. The first provides indications of how increasing population densities result in decreased energy costs per household for grid and mini-grid solutions. The second shows how an increase in population density from 100 to 500 households/km$^2$ results in cost reductions of between 20% and 75% per household for grid based solutions (resp. 5% and 65% for selected mini-grid based solutions).

### 3.3. Local grid connection characteristics

Local grid characteristics influence the least cost energy solution in several ways (Fig. 3). The unit cost of grid transmitted power has a direct influence on the final cost of electricity for each new connected settlement. In countries with lower national electricity costs, demand provision through grid connection will be cost competitive for a larger share of the population as compared to a similar country with higher national electricity costs. The distance between the settlement to connect and the grid connection point will also play a key role in determining the final cost of energy: the costs of grid connection per household and the corresponding LCOEs decrease sharply with the distance to the local connection point. Representing different grid costs for a Tier 3 of energy access, Fig. 3 shows that competitivity of grid connection with other options, for a given settlement, is directly related to the distance between the settlement and the connection point. For instance, with a national grid electricity cost of 0.15 USD/kWh, a 10 km increase in distance to the grid results in LCOEs increases of up to 60%.

Other factors influence the dynamics of grid based system costs. Interactions among neighboring settlements needing energy access can decrease the final cost per connected household. Additionally, cost effective grid extensions are often related to providing electricity to energy intensive productive activities, such as mining. Neighboring residential settlements may then have the possibility of connecting to the grid at a lower cost than if all the grid extension were allocated to residential users only. Additionally the presence of energy intensive productive activities in the settlement to connect could decrease the costs of energy for residential purposes.

### 3.4. Local energy resource availability and technology cost

Local resource availability and fuel costs determine the choice of either stand-alone or mini-grid as the least cost off-grid solution. For a Tier 2 target level of energy access, Fig. 4 shows the comparison between selected mini-grid and stand-alone technologies, as a function of energy resource availability and fossil fuel costs.

[4] Technologies included in the image: 1) GRID: Grid connection in between 10 and 30 km of distance, with national grid electricity prices of 0.15 USD/kWh. 2) MINI-GRID: Diesel MG with Diesel price of 0.75 US$/l, PV based MG with Irradiation of 2000 kWh/m$^2$/year; Mini hydro. 3) STAND-ALONE: Diesel based SA solutions with Diesel prices of 1 US$/l, PV based SA solutions with Irradiation of 1750 kWh/m$^2$/year.

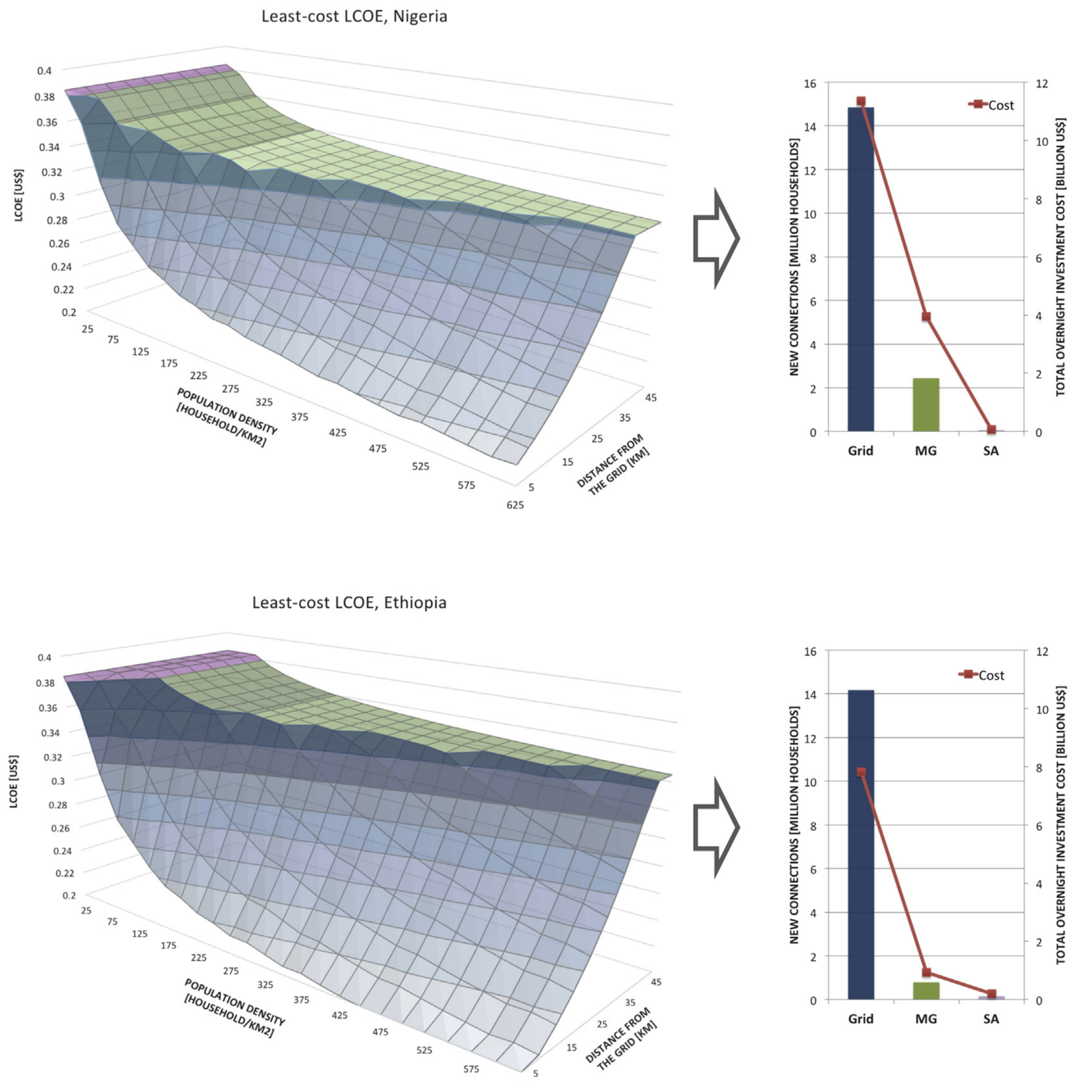


**Fig. 5.** Nigeria (top) and Ethiopia (bottom). Left: least cost LCOEs as a function of the distance to the grid and population density. Right: consequent number of connections and overnight investment for each connection type (right). Stand-alone options are represented in purple, mini-grid options in green and grid options in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Regarding solar energy powered solutions, the cost difference of using the same energy technology under different conditions of solar availability is considerable. For a Tier 2 access level, stand-alone solar systems with a high solar availability (2250 kWh/m$^2$/y) can produce electricity up to 25% cheaper than systems placed in areas with lower solar availability (1750 kWh/m$^2$/y). Similar cost differences occur with mini-grid based solar solutions. Correspondingly, high capacity factors for wind energy systems influence the cost competitiveness of mini-grid based wind solutions: high wind availability (cf $=$ 0.3) can offer LCOEs than most solutions compared in Fig. 4. In parallel, the local cost of diesel also has a significant influence on the LCOEs of diesel-based solutions. For instance, an increase of 0.5 US$/l in the cost of diesel for stand-alone solutions results in an LCOE increase of up to 40%. Finally, the availability of either mini-hydro potential or biomass feedstock (i.e. large livestock) for biogas production near the settlements can provide least cost electricity for population densities over 150 households/km$^2$.

Additionally, a certain variability in capital costs was also taken into consideration. For fossil fuel technologies, most of the costs are associated to the fuel. A 20% decrease in capital costs for fossil fuel based solutions therefore results in LCOE changes of less than 3%. For renewable energy powered mini-grid solutions, a similar capital cost change results in considerable LCOE reductions of 10–15%. Corresponding renewable-based stand-alone solutions see the most significant LCOE change with cuts of up to 20%. Concluding, decreasing capital costs of generation technologies would mostly benefit the cost-competitiveness of renewable energy technologies, and especially of stand-alone solutions.

### 3.5. Applying the cost model: case studies for Ethiopia and Nigeria

Potential applications include fast assessments of single electrification projects, policy advice on energy access, and integration within a geo spatial analysis to evaluate access possibilities in national case studies.

So far, the cost model has been used to inform two GIS-based case studies evaluating least cost energy solutions in Ethiopia and Nigeria. Results were featured in the International Energy Agency World Energy Outlook 2014 [17]. In these case studies, the energy

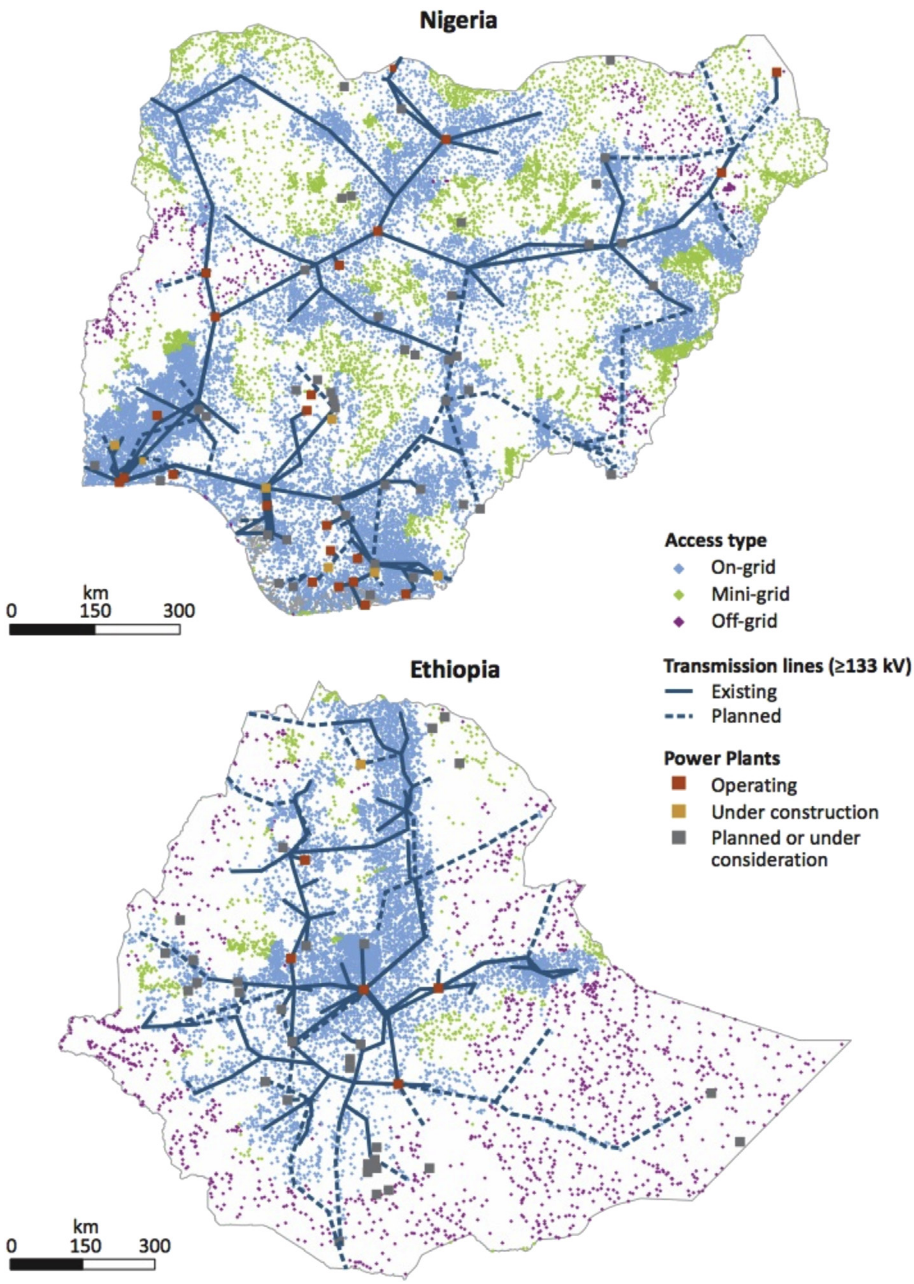


**Fig. 6.** Optimal split by grid type in Nigeria and Ethiopia, based on anticipated expansion of main transmission lines, elaboration of the authors for the IEA World Energy Outlook 2014 [17].

access targets were established according to the IEA New Policies scenario[5] as well as country specific data for local energy resource availability and technology costs. Left hand graphics in Fig. 5 present the least cost electrification solutions as a function of distance to the grid and population density for Nigeria and Ethiopia.

For low population densities, stand-alone options (in purple) are the least-cost solution in both countries. With increasing population density the least-cost solution changes to mini-grid (in green) and grid based solutions (in blue) depending on the distance from the grid.

The different characteristics of Ethiopia and Nigeria influence the results. For instance, the lower cost of grid-electricity in Ethiopia (0.12 US$/kWh) as compared to Nigeria (0.15 US$/kWh) increases the competitiveness of grid connection in Ethiopia making it viable for more combinations of population density and distance from the grid.

In a next step, the graphs were applied to evaluate each GIS settlement[6] of Nigeria and Ethiopia. Descriptions of the GIS data and the methodology used to integrate the cost model into the GIS

[5] For Nigeria, targets of energy access by 2030 were 170 kWh/person/year for rural areas, and 350 kWh/person/year for urban areas. For Ethiopia the corresponding values were 150 kWh/person/year and 350 kWh/person/year respectively.

[6] GIS settlements are areas of 2.5 × 2.5 km.

model is detailed by Mentis et al. [24]. The GIS analysis was performed to derive the least cost split between stand-alone, mini-grid and grid based technologies, as well as investment costs per technology type for the considered energy access target (right graph in Fig. 5).

The majority of households could be electrified cost-effectively with grid-based technologies, which is the least-cost solution for 85% of households in Nigeria and 93% in Ethiopia. This results in considerable investment costs for transmission and distribution of electricity representing 11 and 8 billion US$ in Nigeria and Ethiopia respectively. Mini-grid based solutions are the least cost solution for almost 2.5 million households in Nigeria and 1 million households in Ethiopia. The investment costs per household for MG solutions is higher than for grid based solutions, amounting to 4 billion US$ in Nigeria and 1 billion US$ in Ethiopia. Finally, stand-alone options are the least-cost electrification solution for less densely populated areas (below 50 households/km$^2$). Approximately 60 and 200 thousands households are electrified with SA solutions in Nigeria and Ethiopia respectively, with average investment costs of 1250 US$/household. These results depend on the target of energy access: lower energy access targets would increase the competitiveness of SA and MG technologies.

GIS-based results for the least-cost electrification split between stand-alone, mini-grid and grid-based technologies are reported in Fig. 6.

The map-view shows that even if most households are electrified with grid-based solutions, both countries have large areas where MG and SA based solutions are the least cost option. In fact, grid-based systems are the least cost solution in densely populated areas close to the grid. This results in large numbers of households being grid-connected even though large areas of the two countries – and thus a significant number of households – can be connected in a cost effective way with MG and SA solutions.

Additionally, this country based approach shows that the most cost effective way to expand energy access varies widely both between and within given regions or countries in sub-Saharan Africa. For a given target of energy access results change significantly between the two countries: in Nigeria, a higher population density and a more widespread grid coverage favors on-grid and mini-grid energy supply; in Ethiopia a significantly lower “overall” population density causes stand-alone solutions to play a key role in providing electricity to large areas of the country.

## 4. Conclusions

Considering the limited size of national energy budgets, the transition towards universal electricity access will rely on different combinations of electrification technologies selected based on location specific parameters. The cost model and the approach presented in this paper compare grid, mini-grid and stand-alone solutions across four key parameters, namely: (i) target level and quality of energy access, (ii) population density, (iii) local grid connection characteristics and (iv) local energy resources availability and technology cost. The approach was applied to two country case studies (Nigeria and Ethiopia) to help analyze the implication of reaching different energy access targets.

Analyzing the cost model results offers four main considerations. First, energy access target levels influence the technology choice and the corresponding total cost of household connection. With increasing energy access targets least cost solutions move from stand-alone to grid and mini-grid based options. Model results show that achieving the highest energy access targets (Tier 5) can be fifty to a hundred times more costly than achieving entry-levels of energy access (Tier 1) on a “per connected household” basis. Second, population density is a key factor for the cost-competitiveness of solutions requiring transmission and/or distribution: higher population densities justify larger investment in T&D investments. For instance, an increase in population density from 100 to 500 households/km$^2$ results in cost reductions between 10% and 75% per household connected using grid based solutions. Third, local grid characteristics – namely local grid electricity price and distance between the settlement and the grid connection point – will influence the competitiveness of grid connection for energy access. Additionally, locally bounded characteristics of resource availability, fossil fuel prices and generation technology investment costs will determine the choice of least cost energy technology on a case-by-case basis.

This last aspect was further investigated by applying the approach to two country case studies in Nigeria and Ethiopia. In both cases, the analysis shows that given the considered access target, grid-based options proved to be the least-cost solution for most of the newly electrified households (85% and 93% in Nigeria and Ethiopia respectively). Nevertheless both countries also rely significantly on mini-grid and stand-alone solutions which prove to be cost effective in providing electricity access for areas with low population density. Comparing the two countries, results show how, in rural Ethiopia, a lower population density would favor stand-alone solutions for providing energy access to large areas of the country. These country scale analyses show how the parameters described in this paper can be taken jointly into account to support decision-making for energy access.

Future work may attempt to include a larger choice of energy solutions in the study, and integrate other elements that may affect the provision and costs of energy access. These might include, e.g., environmental externalities or the role of productive activities.

## Acknowledgments

The International Energy Agency (IEA) for contributing to the methodology development and data collection, the Swedish International Development Cooperation Agency (SIDA) for financing the project contribution to IEA World Energy Outlook 2014, and Vetenskapsrådet and ABB for supporting financing the methodology's refinement.

## Annex A. Model assumptions

Note: Even if the focus of the study is not on single technology comparison, but rather on estimating the influence of selected parameters on energy access dynamics, all input data have been chosen to be as representative as possible for the case study under consideration.

Information on single data source can be made available under request to the authors.

The model assumptions are reported in Tables A.1–A.3.

**Table A. 1**
Electricity generation technology parameters used in the model, BC scenario; The capital cost for the first year of the projection was calculated with the most reliable source for small scale technologies, and checked with other sources as indicated below. Cost projections are selected according to the IEA New Policies Scenario recommendations [17], Sources [13,14,25,26].

| Plant type | Investment cost 2015 ($/kW) | Investment cost 2020 ($/kW) | Investment cost 2030 ($/kW) | O&M costs (% of investment cost/year) | Efficiency | Life (years) |
|---|---|---|---|---|---|---|
| Diesel Genset – Minigrid | 721 | 721 | 721 | 10% | 33% | 15 |
| Mini Hydro – Minigrid | 5000 | 4896 | 4751 | 2% | – | 30 |
| Solar PV – Minigrid | 5000 | 4341 | 3547 | 2% | – | 20 |
| Wind Turbines – Minigrid | 3631 | 3523 | 3318 | 2% | – | 20 |
| Biogas Genset – Minigrid | 1252 | 1324 | 1324 | 10% | 33% | 15 |
| Diesel Genset – Stand Alone | 938 | 938 | 938 | 10% | 28% | 10 |
| Solar PV – Stand Alone | 6000 | 5209 | 4256 | 2% | – | 15 |

**Table A. 2**
Transmission and distribution costs in the model, Sources: [13,15,17,27].

| Parameter | Value | Unit |
|---|---|---|
| Life | 30 | Years |
| HV line cost (108 kV) | 53,000 | USD/km |
| HV line cost (69 kV) | 28,000 | USD/km |
| MV line cost (33 kV) | 9000 | USD/km |
| LV line cost (0.2 kV) | 5000 | USD/km |
| Transformers | 5000 | USD/50 kVA |
| Additional Connection cost per household connected to grid | 125 | USD/HH |
| Additional Connection cost per household connected with minigrid | 100 | USD/HH |
| T&D losses | 10% | |
| O&M costs of distribution | 2% | Of Capital Cost/year |

**Table A. 3**
Other model parameters and assumptions.

| Parameter | Value | Unit |
|---|---|---|
| Discount Rate | 5 | % |
| Biogas cost [28] | 0.015 | USD/kWh |

## References

[1] International Energy Agency. 2014 [Internet] [accessed 06.07.15]. Available from: http://www.iea.org/publications/worldenergyoutlook/resources/energydevelopment/accesstoelectricity/.
[2] The World Bank. Global Tracking Framework. [Internet]. Sustainable energy for all; 2013 [accessed 2015 Nov 16]. Available from: http://documents.worldbank.org/curated/en/2013/05/17765643/global-tracking-framework-vol-3-3-main-report.
[3] United Nations General Assembly. Transforming our world: the 2030 Agenda for sustainable development. United Nations – Report 15–15900 (E) 220915. 2015.
[4] Rahman MM, Paatero JV, Lahdelma R. Evaluation of choices for sustainable rural electrification in developing countries: a multicriteria approach. Energy Policy 2013;59:589–99.
[5] Fuso Nerini F, Howells M, Bazilian M, Gomez MF. Rural electrification options in the Brazilian Amazon a multi-criteria analysis. Energy Sustain Dev 2014;20:36–48.
[6] Johnson NG, Bryden KM. Energy supply and use in a rural West African village. Energy 2012;43(1):283–92.
[7] Himri Y, Boudghene Stambouli A, Draoui B, Himri S. Techno-economical study of hybrid power system for a remote village in Algeria. Energy 2008;33(7):1128–36.
[8] Banerjee A, Tierney M, Thorpe R. Thermoeconomics, cost benefit analysis, and a novel way of dealing with revenue generating dissipative units applied to candidate decentralised energy systems for Indian rural villages. Energy 2012;43(1):477–88.
[9] Holtmeyer ML, Wang S, Axelbaum RL. Considerations for decision-making on distributed power generation in rural areas. Energy Policy 2013;63:708–15.
[10] Modi V, Adkins E, Carbajal J, Sherpa S. Liberia power sector capacity building and energy master planning. Columbia University; 2013 [Internet] [accessed 16.11.15]. Available from: http://modi.mech.columbia.edu/wp-content/uploads/2013/09/LiberiaEnergySectorReform_Phase4Report-Final_2013-08.pdf.
[11] Kemausuor F, Adkins E, Adu-Poku A, Brew-Hammond A, Modi V. Electrification planning using Network Planner tool: the case of Ghana. Energy Sustain Dev 2014;19:92–101.
[12] Nagai Y, Yamamoto H, Yamaji K. Constructing low emitting power systems through grid extension in Papua New Guinea (PNG) with rural electrification. Energy 2010;35(5):2309–16.
[13] Energy Sector Management Assistance Program. Technical and economic assessment of off-grid, mini-grid and grid electrification technologies. ESMAP Technical Paper. 2007; 121(07).
[14] Energy Sector Management Assistance Program (ESMAP). Model for Electricity Technology Assessments (META). 2012 [Internet] [accessed 16.11.15]. Available from: https://www.esmap.org/node/3051.
[15] Ruijven Bv, Schers J, Vuuren DPv. Model-based scenarios for rural electrification in developing countries. Energy 2012;38:386–97.
[16] The International Renewable Energy agency. Irena portal on renewable energy potential. 2015 [Internet] [accessed 06.07.15]. Available from: http://www.irena.org/potential_studies/.
[17] International Energy Agency. World energy outlook 2014. 2014 [Internet] [accessed 17.11.15]. Available from: http://www.worldenergyoutlook.org/publications/weo-2014/.
[18] Fuso Nerini F, Dargaville R, Howells M, Bazilian M. Estimating the cost of energy access: the case of the village of Suro Craic in Timor Leste. Energy 2015;79:385–97.
[19] Nussbaumer P, Bazilian M, Modi V. Measuring energy poverty: focusing on what matters. Renew Sustain Energy Rev 2011;16:231–43.
[20] Nussbaumer P, Nerini Fuso F, Onyeji I, Howells M. Global insights based on the Multidimensional Energy Poverty Index (MEPI). Sustainability 2013 May;5:2060–76.
[21] The International Renewable Energy Agency. Estimating the renewable energy potential in africa a GIS-based approach. 2014 [Internet] [accessed 17.11.15]. Available from: http://www.irena.org/menu/index.aspx?mnu=Subcat&PriMenuID=36&CatID=141&SubcatID=440.
[22] The World Bank. World Data Bank. [Internet]. [accessed 06.07.15]. Available from: http://databank.worldbank.org/data/home.aspx.
[23] Szabó S, Bódis K, Huld T, Moner-Girona M. Sustainable energy planning: leapfrogging the energy poverty gap in Africa. Renew Sustain Energy Rev 2013;28:500–9.
[24] Mentis D, Welsch M, Fuso Nerini F, Broad O, Howells M, Bazilian M, Rogner H. A GIS-based approach for electrification planning—A case study on Nigeria. Energy for Sustainable Development 2015;29:142–50.
[25] Info Resources. Sustainable energy – rural poverty alleviation. Focus 2006 [Internet] [accessed 17.11.15]. Available from: http://www.inforesources.ch/pdf/focus06_2_e.pdf.
[26] International Energy Agency (IEA). Energy technology perspectives 2012. 2012 [Internet] [accessed 16.11.15]. Available from: https://www.iea.org/publications/freepublications/publication/ETP2012_free.pdf.

[27] Modi Research Group, Energy Planning Team. Liberia power sector capacity building and energy master planning. 2013 [Internet] [accessed 2015 Jul]. Available from: http://modi.mech.columbia.edu/wp-content/uploads/2013/09/LiberiaEnergySectorReform_Phase4Report-Final_2013-08.pdf.

[28] Khan U, Mainali B, Martin A, Silveira S. Techno-economic analysis of small scale biogas based polygeneration systems: Bangladesh case study. Sustain Energy Technol Assess 2014;7:68–78.