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ELECTRIFICATION PLANNING WITH FOCUS ON HYBRID MINI-GRIDS - A COMPREHENSIVE MODELLING APPROACH FOR THE GLOBAL SOUTH

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Abstract

Electrification of rural areas is one of the major challenges in countries of the Global South. A proper electrification planning requires comprehensive electrification modelling to understand the least-cost supply options. Within this paper we apply a literature research on the requirements of comprehensive electrification modelling. This is extended by research on and testing of existing modelling tools (HOMER Energy, Network Planner, GEOSIM). This analysis reveals that still none of the existing tools can fulfill all requirements combining geospatial and detailed power system modelling especially for hybrid mini-grids. Thus we present our newly developed electrification modelling approach which overcomes the existing gaps.

Introduction

Reliable access to electricity still remains a challenge in many regions in the Global South (IEA, 2015). Advancing renewable energy technologies and storage systems open up novel perspectives for decentralized supply structures of electricity. As a consequence, new planning methods are required to account for innovative solutions comparing existing electrification options.

Conventional options of providing electricity access based on central power generation and the extension of large transmission grids need to be reconsidered taking into account alternative electrification pathways for regions where access to electricity is still lacking or is insufficient (Ohiare 2015, Zeyringer et al. 2015). Such alternatives are represented by hybrid mini-grids which can combine different power generation and storage technologies to efficiently supply local loads (IRENA 2015). The increased options and complexity of rural electrification underline the need of sophisticated planning tools to determine the techno-economic optimized electrification pathway. Only few tools exist for this target and their application is quite rare. Within our research work we identify the requirements for dynamic electrification modelling tools for rural electrification, compare the different existing tools and finally develop our own approach and tool to create a suitable solution to model electrification scenarios.

Methodology

Various electrification strategies of grid extension and decentralized small-scale energy generation exist and have been analyzed by for example Kaundinya et al. (2009) and Bertheau et al. (2015). These two studies stress the complexity of the available options, which require sophisticated decision support tools to identify the optimal electrification solution. In addition, decision support systems are needed for practitioners (Mentis et al. 2015), especially since new stakeholders such as private investors are looking for innovative business models that match the novel opportunities (Cader et al. 2016, Williams et al. 2015).

Different approaches exist for electrification planning. Each of the available tools sets a specific focus on a certain scope and hence incorporates various technology options on the decentralized supply side and handles the option of grid extension or grid supply differently. This diverse nature makes a comparison of different tools challenging. Against that background three different software tools (Tab. 1) on rural electrification planning are assessed.

Table 1: Software tools for rural electrification planning.

Tool	Case study/References	Source
HOMER Energy	Sen&Bhattacharyya (2014)	http://www.homerenergy.com/
Network Planner	Kemausuor et al. (2014)	http://networkplanner.modilabs.org/
GEOSIM	http://www.codea-france.org/art_planif.pdf http://www.ied-sa.fr/index.php/en/documents-and-links/publications/send/3-reports/33-national-electrification-program-prospectus.html	http://www.geosim.fr http://www.ied-sa.fr

This list may not be exhaustive but aims at providing an overview on the most commonly used tools. These tools are evaluated along the following criteria.

Geospatial planning (population, resources, infrastructure (grid))

Electrification planning for rural regions is often challenging due to the absence of accurate data regarding population, electricity demand and geographic location. These parameters can vary significantly for different regions and impact on the optimum electrification pathway. Furthermore, the remote location of these regions are often difficult to access and hence make it time consuming to collect data on the ground. Nonetheless this information is required to carry out sustainable electrification planning. Particularly, distances between villages and the distance and respective pathways to the existing grid need to be considered - hence a spatial approach is required for comprehensive electrification modelling.

Energy system modelling (detailed mini-grid model and load projection, technologies)

The aforementioned spatially resolved analysis allows assessing local socio-economic, infrastructural and resource conditions which helps to identify simple supply options such as grid extension or small Solar Home Systems for which no detailed temporal simulation needs to be carried out. Nevertheless an analysis of decentralized supply options considering different technologies, such as pure diesel grids or hybrid mini-grids with components of solar PV, batteries and diesel generators needs detailed energy system modelling. At least one reference year has to be simulated in hourly time steps to understand the techno-economic feasibility of hybrid mini-grids as electrification option. Thus, another requirement on electrification modelling is the ability to simulate and techno-economically optimize hybrid mini-grids including battery storage.

Technological criteria

Electrification modelling combining geospatial planning with energy system modelling requires a series of input data to generate a realistic scenario analysis. Firstly, the potential demand of electricity needs to be estimated with a *load projection*. This is necessary to design a system which covers this load. If non-electrified regions are assessed no previous information on electricity consumption exist and it can only be estimated on other available proxies such as size of the village, economic activity and by comparing it to similar, already electrified regions. Additionally, it is important that different off-grid *technologies for mini-grids* and criteria for small scale solutions such as *Solar Home Systems* can be selected within the modelling tool.

Finally, the modelling of decentralized options needs to be compared to grid extension. *Grid extension modelling* is required to estimate the potential grid extension pathway, the distance and the related costs. Due to topology, land use and land cover as well as other factors the least cost grid extension is not the same as the shortest geographical distance. Also the hierarchy of connection between single locations depends on this analysis. For analyzing grid extension options the challenge is to account for realistic costs depending on optimum grid extension pathways. These are often influenced by topography or land use. Especially rural remote regions are often difficult to access and it is important to reflect this while calculating grid extension paths and related costs.

The model comparison (Tab.2) shows that each of the tools implements certain aspects of the previously defined criteria. HOMER Energy allows a detailed simulation of diesel and hybrid mini grids. However, this tool provides only a calculation of the breakeven grid extension distance if the costs for grid extension (Capital costs and O&M costs) and the grid electricity costs are provided. This calculation does not suggest on how to spatially connect the respective consumer cluster to the grid and stand-alone solutions are not calculated at all. Due to the missing geospatial planning HOMER Energy cannot sufficiently be applied for electrification modelling.

Table 2: Comparison of different tools based on the described criteria.

Tools	HOMER Energy	Network Planner	GEOSIM
General criteria			
Geospatial planning	no – only coordinates for solar irradiation assessment are incorporated	yes	yes
Energy system modelling	yes	no – only static analysis	yes - cost-benefits optimisation
Technology criteria			
Load projections	yes – loads are created based on input, also deferrable loads are possible	no - load needs to be provided	yes – detailed projection builds on different user classes and surveys
Hybrid mini-grid	yes	no, only diesel based mini-grids	yes – but no solar mini-grid
Stand-alone system	no	yes – solar home system	yes - solar home system
Grid extension modelling	no – only calculation of breakeven grid extension distance	yes – the methodology is built on a Dijkstra's algorithm finding the shortest path between locations which ought to be connected to the grid, but no topographic details are considered	yes – considering constraints such as distance to substations, investment budgets, available energy on the grid, but no topographic details are considered

The Network Planner includes geospatial planning, but this tool does not model hybrid mini-grids, only diesel systems and stand-alone systems (solar PV) are considered. The software does calculate the optimum grid extension between several non-electrified clusters. The methodology is built on a Dijkstra's algorithm finding the shortest path between locations which ought to be connected to the grid. Here it is noted that the shortest path refers to the shortest geographical distance, disregarding aspects such as topography or distance to roads.

GEOSIM allows geospatial electrification planning under within the following framework: Load projections are possible, diesel, biomass and hydro mini-grids can be simulated. Solar power is used for stand-alone systems. Grid extension considers different constraints as the ones described in the criteria section; these are e.g. investment budgets and available energy on the grid. It is the most advanced tool, but lacks the very important feature of simulating solar based hybrid mini-grids.

In summary, each of the presented tools holds certain strengths and weaknesses, for example the lack of detailed demand analysis or of certain renewable technologies. Thus, we developed an approach to include the strengths and to overcome the weaknesses within one comprehensive electrification model which is presented in the next section.

Results

Overview

To fulfill the aforementioned requirements of electrification modelling three main steps have to be conducted. As a first step it is required to assess the status of electrification of a given region. This is followed by a demand analysis to project the required electricity. In the last step electrification options for each location are calculated – which can be hybrid mini-grids with storage options, solar home systems or grid extension (Fig. 1). The analysis is location specific and requires geospatial data sets to account for specific local characteristics. As baseline georeferenced population data are needed to define potential consumer clusters. In the following each part of the planning process is described in detail.

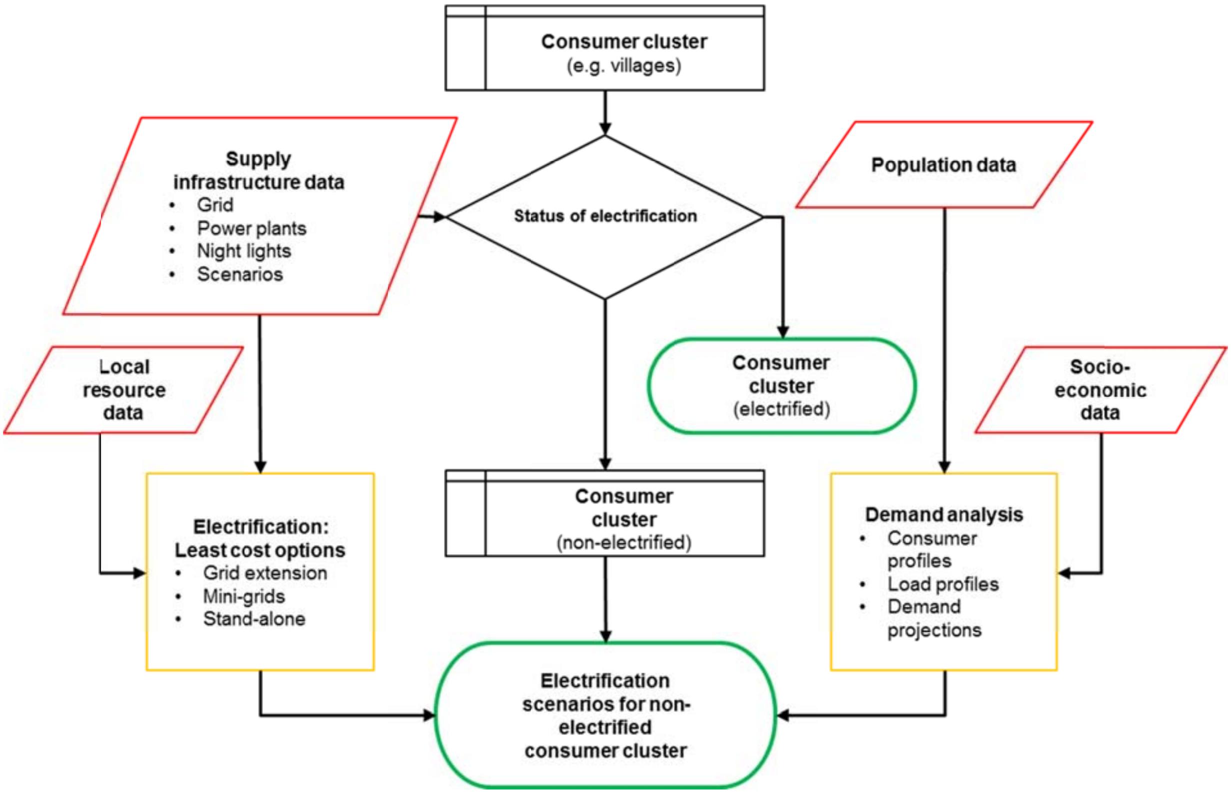

Figure 1: The flow diagram describes a holistic approach to assess different electrification options for developing regions with low electrification levels. This analysis requires a complex set of various input data (symbolized in red) and processing steps (symbolized in yellow). With the provided input data the sample of clusters which need to be electrified is defined. For these locations a demand assessment and the calculation of least costs electrification options is carried out. As result each inhabited location is either already electrified, or the optimum electrification scenario will be suggested (symbolized in green).

Status of Electrification

In regions with low electrification rates detailed data about access to electricity on a village level is often missing. By defining the status of electrification into electrified or non-electrified it is important to bear in mind that electrification is a dynamic progress (Pachauri, 2011). The definition of electrification is non static which is illustrated by the energy access ladder within the multitier framework of access to electricity (Bazilian et al., 2010, Groh et al. 2016). However, to conduct spatial electrification planning over larger geographical entities it is required to simplify the approach. Nevertheless, it is necessary to gain a clear understanding of the actual energy access situation distinguishing among electrified and non-electrified villages or consumer clusters. If recent data or statistics on the power supply and distribution are not available workarounds have to be developed to assess the local situation as exactly as possible. Several different data sets can present a proxy to derive data about electrification. Night light satellite imagery presents one option. A global, cloud free data set on night light emissions with a spatial resolution of 750m x750m is available[1]. This allows drawing a conclusion for electrified areas (Elvidge et al., 1997, Doll&Pachauri, 2010). Only those locations will emit light, which can be tracked by satellite sensors.

In addition, data on energy infrastructure can be used to evaluate local energy access characteristics. The existence of power lines and transformers and of the availability of decentralized power generators can be used to derive the status of electrification. Sometimes, also data on social infrastructure such as schools or health stations are available together with the information on available electricity. Furthermore, some countries inquire about the source of lighting within their national censuses. In case the source of lighting is stated as electricity it is a clear indicator for an electrified region. By using this various indicators it is possible to define regions with their respective population as electrified or non-electrified. Depending on the spatial resolution of all the data it is possible to derive spatially resolved information on the status of electrification. In the optimum case this information is already provided in form of village lists with geographical coordinates or similar. Within our model we consider in any analysis night light imageries which are processed automatically and assigned to each consumer cluster. Additionally, we can easily include other available georeferenced data to improve the assessment of the status electrification.

Demand Projection

After the identification of the non-electrified consumer cluster it is necessary to assess the electricity demand and load profile for each location to enable a least-cost comparison. Common approaches for load projections such as measurements, questionnaires and surveys are

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[1] http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=79765&src=ve

not applicable due to resource and time constraints. Thus, we developed a generic approach which is highly automatized but delivers a high level of accuracy at the same time.

The developed load assessment methodology is based on five steps: Firstly, demographic and socio-economic information is compiled for each consumer cluster. Basic information comprises the number of households and GDP per capita. If further information is available per consumer cluster it can be added. For example, such information can be on education, health and water supply facilities. After compiling this information it is possible to distinguish the consumer clusters in terms of population size and socio-economic development. Secondly, daily load profiles are derived for each consumer cluster based on typical consumer groups. The default consumer groups considered are residential (households low/middle/high income), commercial (shops, small businesses) and productive (small manufacturing).consumer. For each group standardized load profiles and electricity consumption per day are defined. For each of these three groups the respective quantity per consumer cluster is available. As we know the quantity of each group (e.g. 100 low income households) it is multiplied with the typical daily consumption (e.g. 0.5 kWh/day) to form the overall electricity consumption per consumer group and village (e.g. 50 kWh/day for low income households). As special parameter the assumed electricity tariff for the to be electrified consumer cluster can be set which influences the overall consumption as well especially for residential customers. Subsequently, the derived overall consumption is distributed along the typical daily load profile pre-defined per consumer group. After replicating these steps for each consumer group all individual profiles are consolidated to a daily profile per consumer cluster which is then replicated to a yearly load curve by simply repeating 365 days. Thirdly, a seasonal load profile is incorporated reflecting peak demands mainly for agricultural appliances. Thus an annual load profile reflecting the seasonal use of processing machines is created by the usual electricity consumption of these machines and the timely distribution according to the harvesting periods of the target region. Subsequently, the seasonal load curve is added to the yearly load curve derived from the daily load curves. Fourthly, the annual load curve is modified according to random values within a predefined range. This variation of values shall reflect the variations in consumption patterns which exist in reality. Fifthly, the load curve is rescaled based on the overall projected electricity consumption of each consumer cluster. By that 8,760 values of projected electricity consumptions for one year can be derived with the help of our developed approach.

Least-Cost Analysis (Stand-Alone Systems, Hybrid Mini-Grids, Grid-Extension)

As a final step of the electrification modelling the least-cost supply option to serve the projected electricity demand has to be calculated. For each cluster the following three options can be assessed: stand-alone systems, hybrid mini-grids or grid extension.

Stand-alone systems are automatically assigned for consumer cluster with a population and load below a certain threshold (e.g. population below 500 and / or total peak loads below 20 kW). For these clusters it is assumed operating mini-grids or transmission grids is not economically viable. Thus, stand-alone systems for such consumer are suggested which are comprised of solar PV and batteries. Per household a 150 Watt system is chosen which usually provides enough electricity for lighting, cell phone charging and other small devices. In most cases it might occur that the stand-alone systems will not be able to cover the projected demand. This means the load projection shows suppressed demand for these clusters. As techno-economic output for all clusters supplied with stand-alone systems the needed solar-home-system capacity, investment costs, operation and maintenance costs and LCOE are revealed.

For the remaining clusters detailed calculations on hybrid mini-grids and grid extension costs are conducted. *Hybrid mini-grids* are simulated within our developed model based on the derived load profiles and resources. Considered technologies are diesel gensets, batteries (lead-acid or lithium-ion) and renewable resources (solar, wind, hydro) according to availability of input data. The capacities of the single technologies are techno-economically optimized to meet the projected load. Different configurations are simulated for one reference year considering all 8,760 time steps. For each hour of the reference year the load has to be covered by either renewable power, battery discharge and / or diesel power. As an exemption, a special parameter allows for capacity shortage during certain times of the year to reduce the costs of the rural supply systems. Finally, the tool shows the least-cost hybrid mini-grid supply option and can distinguish among diesel only, hybrid, and renewable only solutions. The techno-economic capacities of each considered technology are optimized for each consumer cluster. Output parameters are similar to stand-alone systems: capacities of applied technologies, investment costs, operation and maintenance costs and LCOE.

For the option of *grid extension* spatial data on current electricity transmission infrastructure is required. The developed methodology assesses the costs of connecting the non-electrified consumer cluster to the transmission grid. Thereby information on topography, land use, land cover and distance to existing infrastructure such as roads is considered. Combining and weighting the particular data sets results in one accumulated cost raster. This comprised cost raster has lowest values for the most favorable characteristics for grid extension (e.g. low slopes, closeness to existing infrastructures). In addition, it is possible to define exclusion zones such as water bodies or national parks by allocating extremely high costs to these locations. By applying a routing algorithm least cost paths are calculated on how to connect all clusters to the existing grid infrastructure. In order to elaborate the optimum connection paths for all clusters a minimum spanning tree is created using the least cost paths. By assessing the distance of the derived connections path the grid extension costs can be calculated for each cluster supplying the projected loads. Again, investment costs, operation and maintenance costs and LCOE are calculated as well as the needed grid capacities. By that last step the comprehensive electrification modelling is concluded and shows least-cost electrification options for all identified non-electrified consumer clusters. Results can be made available in lists or directly in dynamic maps which and can be integrated in database management systems.

Discussion and Conclusions

Within the second section we have analyzed the requirements on electrification modelling tools and concluded in the need of a new developed as not all requirements are fulfilled by the presented existing tools yet. With our developed tool a very high number of consumer clusters can be automatically analyzed and least-cost electrification options are assessed. It combines both geospatial planning and detailed energy system modelling especially for hybrid mini-grids including different storage options. Especially for remote regions our tool reveals the techno-economic potential of decentralized off-grid options compared to the conventional grid extension. This is due to the inclusion of different mini-grid set-ups which allows suggesting cost competitive hybrid mini-grid solutions and due to the inclusion of detailed grid extension costs which reduces the competitive advantage of grid connection as electrification option. For this comparison the detailed load projection is a prerequisite and therefore included in our model as well. Thus, the presented new model fulfills all the elaborated criteria for comprehensive electrification modelling. In addition, it only requires open access software such as QGIS[2] and Python[3] which allows a broad application without expensive software licenses. The model is currently applied for electrification modelling and planning in Nigeria. Preliminary results proof the applicability and validity of the model for rural electrification (Bertheau et al., 2016). Based on the high flexibility of the model it can easily be adapted to the conditions in other countries of the Global South.

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[2] http://www.qgis.org/de/site/

[3] https://www.python.org/psf/

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