Microgrids-as-a-Service for Rural Electrification in Sub-Saharan Africa

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Abstract: The majority of the population on the African continent is unable to access basic electricity services, this despite the abundance of renewable energy sources (RESs). The inability to adequately tap into these RESs has led to the continued dependence on non-renewable energy sources such as coal for electricity generation, and kerosene for cooking and lighting, the resulting use of which is poor health conditions. The use of Microgrids (MGs) is being extensively researched as a feasible means of tackling the challenge of electrification, especially in rural and remote areas. Recent times have seen an increasing number of research works focusing on Sub-Saharan Africa (SSA), which is one of the regions with the lowest electrification rates in the world. MGs provide the most suitable means to integrate RESs into the electricity generation process, paving the way towards clean energy for the African continent. This paper presents a review of recent literature on the usage of MG technology for rural electrification, with a specific focus on the applicability of MGs in the SSA context. The paper additionally presents the challenges and opportunities to date. Research findings indicate that SSA has already begun the transition towards clean energy via implementation of RES-based MGs. However, two resonating challenges in the literature are adequate support via policy, and proper planning of project implementation. These two major barriers are needed to be overcome in order to fully utilize MGs for rural electrification in SSA. The key methodology derived from this study is that any effort towards rural electrification requires a sufficient amount of investigation, incorporating both the technological and socio-economic aspects into a suitable design for the target location.

Keywords: Microgrid, rural electrification, Sub-Saharan Africa.

1 Introduction

Universal access to electricity remains to be one of the greatest global challenges that needs to be addressed to date. The International Energy Agency (IEA) [IEA (2018)]

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recently reported that the majority of the 1.1 billion people worldwide who are unable to access electricity services today, reside within Sub-Saharan Africa (SSA). Another finding was that 2.8 billion people continue to depend on biomass, coal, and/or kerosene to sustain their daily activities inclusive of cooking and lighting. The use of these energy sources in known to result in household pollution, which has been linked to 2.8 million premature deaths per year. The reliance on the aforementioned energy sources is said to also greatly hinder productivity, with several billions of hours spent collecting firewood for cooking, mostly by women, hours which could be better utilized for personal, regional, and national development.

There are number of electrification projects that have been and are currently being initiated and implemented across the African continent, with the World Bank and United Nations playing a major role. The main initiative has been Sustainable Energy for All (SEforALL) which is a joint operation between the two entities aiming for: 1) universal access to electricity, 2) higher energy efficiency in homes and businesses, and 3) larger contribution of renewable energy to electricity generation worldwide [SEforALL (2018)]. Another well-known initiative is Power Africa, which is facilitated by the USA government and aims to provide suitable solutions for this pressing issue [Power Africa (2018)]. Despite the efforts of these initiatives and other lesser-known projects, there is still a large amount of work that needs to be done, and in particular there is a need for technologically viable and scalable solutions for SSA.

When considering the recent trends in technological advancements, Cyber-Physical Systems (CPSs) and Internet of Things (IoT) are revolutionizing the interaction between the cyber world and the physical world [Lin, Yu, Zhang et al. (2017)]. The developments in the energy sector are seen as a key determining factor that will redefine the way we view energy usage, both locally and on a global scale. IoT is at the forefront of the transformation of electric power and energy systems (EPESs) to provide clean distributed energy for sustainable global economic growth. The key benefits of IoT integration in the electricity generation, and transmission and distribution (T&D) processes are greater efficiency, reliability, security, resiliency, and sustainability [Bedi, Venayagamoorthy, Singh et al. (2018)].

The most representative application of the integration of CPS and IoT with regards to electrical energy usage is the Smart Grid, which embodies the ideology of a new way of generating, transmitting, and distributing electrical energy. The Smart Grid provides bidirectional flow of electricity and information between connected entities and utilizes a variety of technologies to ensure reliable and flexible access to electricity. The Microgrid (MG) is an essential component of the Smart Grid, and provides a platform for increased delivery of electricity services via a mixture of energy sources, with greater inclusion of renewable energy sources (RESs). According to the USA Department of Energy (DOE) [USA DOE OEDER (2012)], installations of distributed energy resources (DERs) which adhere to the following three criteria, can be classified as MGs: 1) presence of clearly defined electrical boundaries, 2) presence of a master controller which manages the DERs and loads as a single controllable entity, and 3) ability to sustain the provisioning of electricity services when connected to or disconnected from the main grid. Suitable implementation techniques of MGs for electrification are being actively researched on a global scale. This surge in interest has been driven by the need to reduce carbon emissions, and the desire for alternatives to the current structure of electricity generation, and T&D.

MGs provide the means through which we are able to fully realize the integration of DERs in the electricity generation, and T&D processes. This fact coupled together with the lowering prices of low-carbon technologies shapes a future which enables a larger percentage of inclusion with regards to electricity access. In addition, their ability to operate in connected mode and islanded mode opens up a lot of possibilities. These possibilities include reliable transmission during or after faults in the main grid, caused by accidents or natural disasters, and improved availability of electricity due to the ability of MGs to act independently of the main grid. Another added benefit is that initially islanded MGs in remote areas can be integrated into the main grid once the main grid has reached a suitable level of expansion. MGs present a great opportunity to help foster the electrification of rural regions in SSA. They enable reliable provision of electricity by integrating various sources of energy which are in abundance in SSA, and have the ability to scale with demand which makes them suitable to grow in response to the development of rural areas. Given the enormous socio-economics benefits of solutions to rural electrification, this research area has seen active participation across the globe. Such benefits include improved productivity and security via lighting, use of clean energy for cooking, improved telecommunications for remote areas, and community development via improved methods of irrigation for agriculture and provision of basic services dependent on electricity.

This paper presents a review of the recent approaches utilized for the application of MGs towards rural electrification in SSA. The main contributions of this work are to highlight promising approaches, and propose guidelines for future developments towards rural electrification in SSA. Section 2 presents an overview of MGs, and DER technologies. Section 3 provides a study of the recent research work that has been conducted with regards to rural electrification, with the main focus being on the works conducted in SSA. In Section 4 we present a summary of the current challenges and opportunities towards rural electrification, and we conclude our research findings in Section 5.

2 Microgrid overview

2.1 Architecture

The architecture of a MG typically consists of loads, DERs, a master controller, smart switches, protective devices, and communication, control, and automation systems. Loads can be fixed or flexible, with fixed loads needing to be satisfied under normal operating conditions. DERs are classified into distributed generation units (DGUs) which include energy generation sources, and distributed energy storage systems (ESSs) which assist with prolonging electrical energy generated within the grid, and provisioning of electrical energy during periods which there is a shortfall. The master controller oversees the operation of the MG and its resources in both connected and islanded modes, and interacts with the switch at the point of common coupling (PCC) to connect to and disconnect from the utility grid. Protective devices, and communication, control, and automation systems work hand in hand to ensure the optimal running of the MG in both normal and abnormal working conditions. An example of the aforementioned architecture can be seen in Fig. 1.

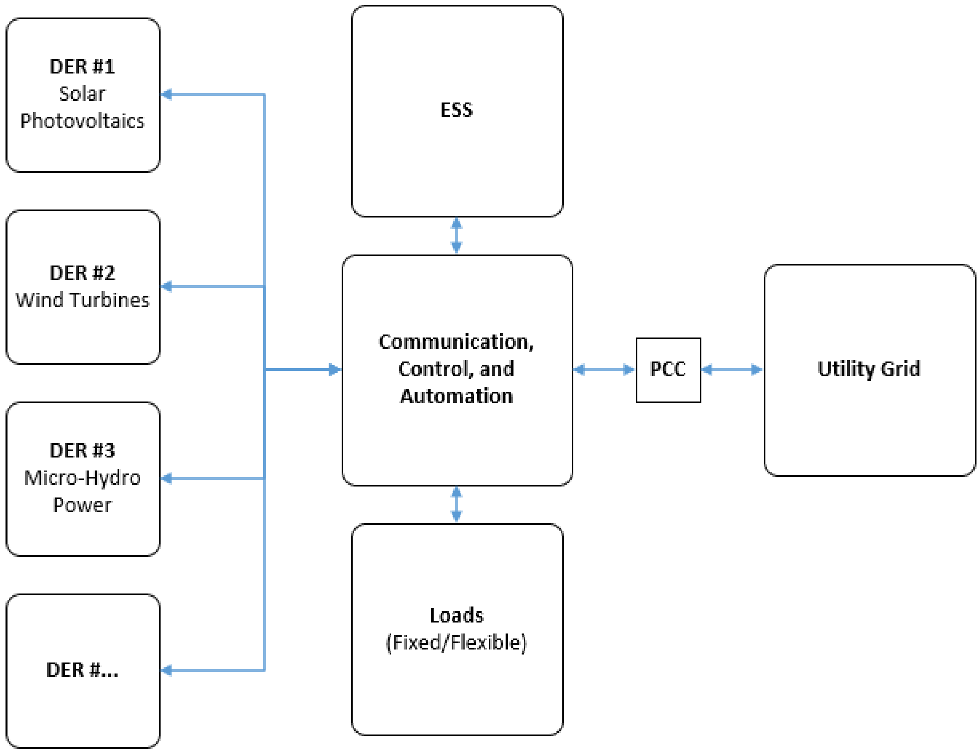

Figure 1: Example Microgrid architecture

2.2 Energy sources

There is a wide variety of energy sources (ESs) available for use in MGs, providing a wide spectrum of configurations, with the designs constrained to the feasibility of utilizing the local energy sources when considering the target site. The DGUs that are commonly integrated into MGs include solar photovoltaic (PV) array, wind turbine (WT), micro-hydro power (MHP), geo-thermal source (GS), thermoelectric generator (TG), tidal or wave energy generator (TWG), biomass energy generator (BEG), and combined heat & power (CHP) generators. Diesel generators (DGs) are additional ESs which typically serve as a conventional back up for MGs. Rezkallah et al. [Rezkallah, Chandra, Singh et al. (2017)] enumerated a number of configurations for MGs classified on the basis of the preferred ESs. They considered the use of up to four ESs in the grid design, targeting usage in remote areas.

Rural regions in Southeast Asia and Africa are said to receive abundant sunlight, above 5.5 kWhr/m^2 per day for most regions [Jaffery, Khan, Ali et al. (2014); Khan and Arsalan (2014)]. This coupled with lowering prices for solar PV equipment has made electricity generation utilizing solar PV an attractive alternative to conventional methods. Other commonly cited ESs for rural electrification are WT, MHP, and DG.

3 Microgrids for rural electrification

Wang et al. [Wang, Lee, Chen et al. (2009)] presented a 3 kW MHP system which made use of two self-excited induction generators (SEIGs) and the irrigation water flowing in a ditch. The results of experiments using various values of steady-state measurements such as water-flow rate, and excitation capacitor bank, and dynamic measurements such as SEIG rotational speed, and braking system indicated that MHP can be a useful energy source for rural electrification in Africa. It was additionally demonstrated that MHP can be a financially viable solution for electrification utilizing water resources.

Despite having a large economy, Nigeria is said to fall short in meeting the electricity demands of its population. Ogunnubi et al. [Ogunnubi, Ajala and Idehen (2017)] proposed a Microgrid-as-a-Service (MaaS) framework to address these shortcomings, by making use of existing generation sources that were in use by the public in urban areas. The framework grouped the energy generators into MGs which addressed the load demands for those within close proximity. The proposed design further enabled the addition and removal of energy sources and loads, building on the concept of plug-and-play (PnP). This allowed for growth of both electricity generation capacity and energy demands met. The use of existing energy generators within a region was also investigated by Soltowski et al. [Soltowski, Bowes, Strachan et al. (2018)]. The study echoed the integration of existing generation sources as a feasible solution to address energy demands, and highlighted that low voltage distribution networks are a suitable means for transmission and distribution within such systems.

Kwaye et al. [Kwaye, Bendfeld and Anglani (2015)] investigated the potential of RESs for electrification in Cameroon. Their findings showed that the northern parts of the country had high wind potential, indicating that northern Cameroon are suitable target locations for the use of WT-based MGs for electrification purposes.

Challenge Driven Education (CDE) was utilized to design an intelligent DC MG that can satisfy the energy demands of small communities in the rural areas of Tanzania [Rwegasira, Kondoro, Kelati et al. (2018)]. This work was part of a project called iGrid which made use of IoT and agent-based architectures in order to design a solar-powered MG that is efficient, reliable, autonomous, and self-sustaining. The outcome of the project work indicated that the combination of research, innovation, and creativity are key factors which bring development in the community.

Patel et al. [Patel and Chowdhury (2018)] studied the use of MHP as a suitable ES for rural electrification in South Africa. The results of their analysis revealed that the strength of a resource impacts the Levelized Cost of Electricity (LCOE), with an increase in strength of a resource reducing the costs of implementing the system. The results also highlighted that the LCOE for an implementation requiring a new dam to be built, is approximately double that of when one already exists. This indicates that utilization of existing dams can result in significant savings in implementation.

For MG business models to succeed, appropriate customers need to be identified and connected in order to sustain the business. Otieno et al. [Otieno, Williams and McSharry (2018)] researched the sustainability of MGs from the business perspective. The authors examined customer data spanning a period of nine months collected from four MGs in Tanzania, in order to discover distinguishing characteristics of the customers. Empirical evidence showed that demographic surveys conducted before MG design are valuable sources of information, with derived demographic variables being useful in classifying customer's connection type, and also for predicting average hourly consumption.

The use of DC has begun to regain popularity in recent times, especially with its suitability for the rural electrification scenario. Hamatwi et al. [Hamatwi, Nyirenda and Davidson (2018)] presented a hybrid DC MG made up of solar PV, WT, DG, and a backup battery bank. The MG was designed for the remote village of Oluundje in northern Namibia. Simulation results of the electrical production added up to 330,097 kWh per year, of which the solar PV, WT, and DG contributed 50%, 21%, and 29%, respectively. Their economic and environmental impact evaluation indicated that the hybrid MG with 71% renewable energy penetration was cost effective in the long run, and it avoided/eliminated 35 tons of greenhouse gases (GHGs) emissions when compared to a solar PV and DG hybrid system. In their work, Loomba et al. [Loomba, Asgotraa and Podmore (2016)] advocated for the use of DC MGs for rural electrification, and more importantly as a medium for sustainable rural development. The basis of this was the fact that DC MGs were 25%-30% more efficient than AC MGs. Hamza et al. [Hamza, Shehroz, Fazal et al. (2017)] presented a methodology for selecting an efficient distribution architecture for solar PV based DC MGs, with respect to village orientation. The results of their analysis suggested the adoption of the O-architecture in linearly distributed villages, and Cluster-architecture for those with a non-linear spatial distribution of houses. Giraneza et al. [Giraneza and Kahn (2015)] researched an approach based on intermediate low voltage direct current (ILVDC) in order to facilitate bottom up grid extension. The proposed method made use of swarm electrification concepts, and aimed to build local grids via MG technology, with the possibility of integration into the utility grid at a later point in time. Local interconnection of generators created a power-sharing scheme which was said to enable those who were less fortunate to access electricity services as long as they were able to pay for the set tariffs. Nasir et al. [Nasir, Khan, Hussain et al. (2017)] proposed a scalable DC MG architecture for purposes beyond those related to subsistence-level living. The grid architecture consisted of several nanogrids capable of self-sustained generation, storage, and bidirectional flow of power within the MG. The results of their analysis showed that the proposed architecture enhanced distribution efficiency by approximately 5% when compared to other low-voltage direct current (LVDC) architectures.

Cronje et al. [Cronje, Hofsajer, Shuma-Iwisi et al. (2012)] explored the usage of MG technology utilizing distributed control for electrification of remote rural areas, and peri-urban areas with a supply deficit. The results of their research identified that suitable design of distributed communication, control, and automation subsystems was a significant hurdle that needed to be overcome for successful implementation in the target regions.

Adetunji et al. [Adetunji, Akinlabi and Joseph (2018)] proposed an alternative ES for the community of Tafelkop, a town located in Limpopo, South Africa. The goal of the study was to sustain the community during intermittent utility grid outages, while incorporating high efficiency, low-cost, and minimal emissions. The proposed solution made use of estimated daily load profile, solar global horizontal irradiance (GHI), clearness index, average load, tariff, and grid outage parameters as inputs to the model.

Buque et al. [Buque and Chowdhury (2016)] examined grid resiliency in Mozambique, with the aim of identifying weak points in the country's grid infrastructure that could be addressed via MG technology. It was determined that northern Mozambique presents the biggest opportunity for improvement of grid resilience, and the authors proposed solar PV based MG configurations as one of the possible means to achieving this. Given Mozambique's unique location, successful implementation of MGs has significant positive impact on not only the nation's development, but also the development of those countries in southern Africa which would draw power from the country's utility grid.

Williams et al. [Williams, Jaramillo, Campbell et al. (2018)] assessed MG customer segmentation in Tanzania according to electricity consumption behavior. The authors made use of the k-means clustering algorithm, and groupings of a) less than 140 Wh, b) 140 Wh to 450 Wh, and c) greater than 450 Wh, in order to derive insights from the customer data. Their findings showed that strong daytime usage was valuable for the system as these hours corresponded to periods in the day with significant solar generation, which in turn reduced energy storage requirements. Another key finding was that a good understanding of the characteristics of the customers across different consumptions patterns can assist with shifting customers from one consumption grouping to another, which could possibly ease the burden on the MG infrastructure.

Otieno et al. [Otieno, Williams and McSharry (2018)] focused their work on forecasting energy demand, which is information that is seen to be critical for designing scalable MGs. The authors based their work on daily energy consumption data derived from seven MG operations in Kenya between 2014 and 2017, and were able to determine that exponential smoothing offered the best out-of-sample forecasting performance, with a forecast range of up to four months ahead.

Real-time monitoring is an essential process to help ensure the correct operation of a system. Remote Monitoring (RM) takes this a step further by eliminating the need to be physically present at the location where the system is running. Given that MGs used for rural electrification are likely to require monitoring by stakeholders not physically located at the target site, there has been research interest focusing on suitable solutions in order to address this challenge. Louie et al. [Louie, Goldsmith, Dauenhauer et al. (2016)] discussed the technologies, applications, and considerations involved in realizing suitable RM techniques for rural MGs. Through their work the authors demonstrated the feasibility of using rural cellular networks as a transmission medium for system data to enable off-site system monitoring and analysis. Given the transmission mediums available in rural areas and the importance of data accuracy, data quality controls are of great importance. Techniques such as the dual-spline approach [Liu and Liu (2018)] can be additionally employed to ensure the correctness of the system data.

Nwulu [Nwulu (2017)] presented a hybrid MG configuration which included CHP, solar PV, and a battery storage system (BSS). The research work aimed to assess the extent to which the inclusion of BSSs affects the design and implementation of MGs. The results highlighted that the addition of BSSs provided a storage medium for electrical energy within the MG, and ensured that there was a backup power supply when it operated in islanded mode.

Backes et al. [Backes, Idehen, Yardley et al. (2016)] developed a hybrid MG system which made use of solar PV, WT, and GS as ESs, designed for the electrification of the rural village of Katumbi in Tanzania. The results of simulations conducted using real time digital simulator (RTDS) showed that the MG was able to withstand a variety of disturbances, and addressed the energy needs of the village. The MG was designed to scale well with the growth in demand for community resources which included a hospital, freezers to store the catch of fishermen, a school, and a tower for wireless communication within the community.

Lai et al. [Lai and McCulloch (2017)] presented a MG configuration that used solar PV, an ESS, and anaerobic digestion (AD) biogas power plant (BPP) as ESs. The research work showed that a hybrid system would be cost effective as compared to an AD-only system, when the discount rate applied to low-carbon and renewable generation technologies dropped below 8%.

In the context of Africa and rural areas in general, MGs have a high potential for social and environmental good. Avrin et al. [Avrin, Yu and Kammen (2018)] proposed a framework that could be used to maximize the likelihood that electricity provisioning will lead to positive social and environmental outcomes. The authors applied the framework to communities in the Democratic Republic of the Congo (DRC), with the aim of designing tailor-made MG configurations that address the social and economic inequalities apparent among the Congolese population.

Orajaka [Orajaka (2013)] presented the Green Village Electricity Project as a suitable model for providing solar PV based electricity to remote settlements in Nigeria. The author's case study on the Niger-Delta presented a bottom-up scenario of the actual needs and expectations of inhabitants of rural West Africa, paving the way for future development projects in the region.

Lukuyu [Lukuyu (2012)] proposed a hybrid MG using WT and DG as ESs for the electrification of the village of Marsabit, in northern Kenya. The results obtained from the author's analysis showed that the proposed MG was more reliable when the DG capacity was increased, as opposed to WT capacity, in order to meet growing energy demand. This was due to the fact that the wind power tended to have a low capacity factor and an intermittent nature.

Onai et al. [Onai and Ojo (2017)] proposed a vehicle-to-grid (V2G) technology assisted MG as a solution to the shortfall of clean energy usage in Ghana. Plug-in Electric Vehicles (PEVs) were revealed to be capable of acting as ESSs, and were shown to enhance the operation of the MG in islanding mode as they kept voltage and frequency within acceptable limits of operation.

Experience garnered from various MG designs and projects implemented across the globe have resulted in growing interest to develop frameworks that help to create sustainable MGs irrespective of their purpose and target region, with increasing research focusing on frameworks for rural areas [Kumar, Singh, Deng et al. (2018); Namaganda-Kiyimba and Mutale (2018); Ireland, Hughes and Merven (2017); Kumar, Sah, Deng et al. (2017); Doorsamy, Cronje and Lakay-Doorsamy (2015); Xu and Chowdhury (2013]. These frameworks provide step-by-step guidance that highlight the path towards successful MG implementation and operation, inclusive of considerations for the types of ESs that will be used.

4 Challenges and opportunities

4.1 Challenges

The design and implementation of MGs for rural electrification is a multi-faceted task. The main considerations are policy, politics, social, financial, and technical.

Approaches to rural electrification via MGs first and foremost need to be backed by policy. These policies need to adequately detail the works/projects that can be carried out and the processes that they are comprised of. A definition of stakeholders and participants and the roles they take is also necessary to commence and maintain the necessary work. A large number of nations in SSA maintain a structure where a state owned company has a monopoly on the national grid and therefore electricity generation, and T&D. This usually means that policies to enable the implementation of MGs do not currently exist, or are limited in their writing. Governments therefore need to present an adequate policy framework which will empower the use of MGs for rural electrification and the emergence of suitable stakeholders.

Politics plays a major role in the realization of electrification projects. Furthermore, the progress of such projects can be subject to presidential terms, as those in charge of the country define the goals for the duration of their time in power. It is therefore imperative that rural electrification efforts via MGs receive continued support across presidential terms from the respective government and various recognized bodies that can help to drive the projects through to their envisioned capacity. Another challenge is political stability, which can have adverse effects on project implementation, and operation and maintenance (O&M), with the magnitude of the effects depending on the severity of instability.

When considering rural areas in Africa, the social aspects play a vital role and can make or break projects. Literature strongly suggests the buy-in of the local population and the establishment of a solid relationship that turns into future growth in demand. The needs of the local populations need to be well-defined so as to ensure successful implementation.

As with any implementation the bottom line is the costing. The MG needs to be cost-effective and self-sustainable, which mainly entails maximizing the return on investment (ROI), and minimizing the O&M costs. The recommendation in literature is to thoroughly investigate the target area and gain a solid understanding of it by using geographic and demographic data. Such an investigation provides stakeholders with better information and can help to solidify their buy-in. This work is normally done via surveys and consultations with various experts.

With various advancements in enabling technologies for IoT, there are a wide number of possibilities for MGs today. The main challenge with SSA, and rural areas in particular, is the lacking ICT infrastructure. Therefore, the MG configurations that are put in place need to be robust and integrate the capabilities of their operating environment into the design. A well-known challenge is availability of adequate internet services which is normally used for communications and monitoring of system health. The integration of GSM technology in the MG architecture is one possible solution which can address such an issue.

4.2 Opportunities

The African continent provides a unique landscape requiring innovative solutions due the limited capacity with regards to infrastructure and economic operations. SSA presents the opportunity for researchers to truly define resilient MG solutions that make full use of available RESs while fully incorporating the diversity of the local population. Such solutions expand upon the capabilities of the Smart Grid, and CPSs and IoT in general. The African continent has limited access to internet and thus GSM, 2G, and 3G are communication technologies that can be integrated into solutions to fully realize capabilities such as remote monitoring of systems. Furthermore, with the increase in usage of mobile money platforms across the continent, its integration into the financial workings of MG implementations could prove to be beneficial to project success.

We recommend the approach utilized in the framework proposed by Kumar et al. [Kumar, Singh, Deng et al. (2018)] in order to fully realize the appropriate MGs for various rural areas in SSA. The framework consists of four stages: 1) selection of energy alternatives using decision analysis tools, 2) load growth projections, 3) detailed techno-financial analysis of energy system, and 4) application of decision analysis tools for final project selection. Taking such steps should ensure the successful implementation of MG projects for rural electrification.

5 Conclusion and future work

This paper discussed the various methods and techniques that are currently in use and are among the most viable to solve the rural electrification problem in Sub-Saharan Africa, through the use of Microgrid technology. Given the enormous socio-economic benefits to rural populations and developing nations, the importance of the research work in this field of study cannot be understated. Furthermore, sufficient solutions to electrification in rural areas present further steps toward the envisioned Smart Cities, integrating a wide range of services far and wide. While there are number of challenges that are still to be addressed, the utilization of Microgrids seems to be an important step towards improving universal access to electricity.

For our future work we aim to perform a case study on a country in Sub-Saharan Africa. The proposed work will entail the design of a Microgrid which utilizes solar photovoltaic energy sources and an energy storage system in order to provide electricity services to the local population.

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