Pathways to Universal Electricity Access for Rural Communities in Africa

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Abstract. This paper presents results covering the efficiency of appliances to support reduce power needs in both mini grids and upgradeable solar home systems. In addition, the research has compared the efficacy of DC vs AC mini grids at different scales. In general, the results indicated that DC mini grids could compete well at sites with a smaller geographical footprint, providing efficient appliances are integrated at system implementation. At the higher ‘tiers’ of electrification, we also present results and experiences from the five e4D solar photovoltaics (PV) mini grid projects in Kenya and Uganda. The work includes analysis of community engagement, electrical load characterisation, and system operation of the mini grids in rural settings. The results indicate that energy consumption varies significantly between the sites, associated with socio-economic factors, whilst all the villages’ trading centres have experienced varying levels of business growth. Overall outcomes from this research provide clear indications that mini grid interventions not only invigorate rural communities by enhancing education and health provisions, but are also associated with growth in existing businesses and the creation of new businesses. Therefore, it is recommended that where needed, rural electrification policies be amended to give priority to facilitate and attract investment in decentralized mini grids.

1. Introduction

Access to electricity is pivotal for socio-economic development. Key aspects of Human Development Index (HDI), long and healthy life; being knowledgeable; and having a decent standard of living, cannot be achieved without modern electricity services. The United Nations Sustainable Development Goals (SDG), especially SDG7 aims for universal access to affordable, reliable, sustainable and modern energy for all by 2030. Despite continuous progress, globally 840 million people lacked access to electricity in 2017, most of which are in sub-Saharan Africa (SSA) and South Asia [1]. With the current electrification trend in these regions, almost 650 million people will still remain un-electrified by the 2030 and 90 percent will be in the SSA countries [2]. Global electrification growth peaked between 2015 and 2017 at 1.04%. The required steady annual average increase of 0.86% until 2030 for universal access might be hindered by the slow progress in many high access-deficit countries [1].

Multi-tier frameworks (MTF), the new paradigm for measuring energy access introduced in SE4All’s Global Tracking Framework (GTF) 2013, was further updated in ‘Beyond Connections: Redefining Energy Access’ report [3]. ‘Beyond connections’ redefined the MTF energy access around different attributes of scale. These are: peak capacity, availability (duration), reliability, quality, affordability, legality, and health and safety for applications in lighting, operating electrical and electronic appliances, space heating, cooling and cooking. Broadly, the levels of electricity access are defined as follows: Tiers
1 to 2 span small solar lanterns up to solar home systems (0-200 W); Tiers 3 or 4 would usually be provided by a mini grid or generator (200-2000 W) whereas Tier 5 requires full grid electrification. Facilitating MTF at a global scale three different levels of framework approaches, (i) immediate, (ii) simplified and (iii) comprehensive can be applied for electrification of households, businesses, productive applications and organisational uses [3]. With rehabilitation and future capacity expansion options of the existing off-grid energy systems, access to electricity can be served at higher tiers.

Depending on the definition, energy poverty does not always necessarily refer to economic poverty. This delink is evident from the fact that as of 2016, 120 million people in SSA and 70 million in developing Asia living above the poverty line still had no access to electricity [4]. However, accelerated political commitments at global and national levels towards universal energy access by 2030 in the recent years, coupled with technology leapfrogging (renewables, mobile networks); suitable policy frameworks and innovative business models, have already established decentralised off-grid solutions as competitive and cost affective to grid extension. In 2017 alone, about 120 million people living off-grid gained limited access to the Tier 1 level of electricity supply through solar lights and nearly 34 million gained access to above Tier 1 level through solar home systems and mini grids [5].

Although PV technology has matured, the notable growth rate of off-grid electrification access in SSA may be hindered if the interrelated dynamics (i.e., technology, suitability for applications, quality of components, quality of appliances, efficiency, socio-economic conditions, policy framework, business delivery and financing models) are not well understood and appropriate actions taken in time to mitigate impacts of such dynamics. Poor quality of appliances, PV modules, and battery systems and maintenance issues are evident in a number of reports and literature [6]; [7]; [8]; [9].

2. PV based off-grid electricity access systems

A recent report indicates that during in the second half of 2019, around 2.59 million solar lighting products were sold in African Market compared to 1.57 million in Asia [10]. Innovative payment options such as mobile money or digital payment based Pay-as-you-go model and improved efficiency in end-use products (PV panel, battery, power electronics, LED bulbs and other appliances) combined with wider development impacts (income generation, quality of life and well-being) have accelerated the take-up of the small solar system sales in Africa since 2009 [11]. At present, this market is dominated by private sector which is a big shift from donor supported niche. However, lack of regulatory framework to enforce quality standards across this region, the market is being flooded by unbranded low quality products [12]. Quality issues of PV components and commonly used appliance will dent user confidence in this approach of electrification which would in turn delay SDG 7 target.

Although direct current (DC) is native to photovoltaic electricity generation and many of the commonly used off-grid appliances (e.g. LED lighting, TV, fan, refrigerator) are inherently DC in nature, DC mini grid (DCMG) based electrification is very rare in developing countries. With the decreasing cost of PV and increased efficiency of DC appliances, DC mini grids may provide a cost-effective way to deliver electricity to off-grid areas. The topic of DC mini grids is an active area of research with the focus on the design, stability and efficiency aspects of DC power systems and DC mini grids [13]; [14]; [15]; [16]. Sharp et al., [17] studied DC mini grid architecture, operation, performance and limitations and compared such system costs to traditional electric power delivery models in developing regions. Their study concluded that such mini grids can provide sufficient electricity to power LED Lighting, cell phone charging, radio, TV, portable computers, water pumping and cooking. Greater design and space flexibility of DC mini grids are identified in many literature and reports [18]; [19]; [20] and [21]. However, limited DC appliances availability in the market especially in Africa poses as a major challenge [22]. The use of DC 12-volt LED light bulbs powered by electricity generated from PV can provide savings of up to 30% in consumption by eliminating the use of inverters and the unnecessary DC-AC-DC conversion [23]. Phadke et al. [24] claimed that super-efficient DC appliances can lower total energy costs by as much as 50% compared to existing AC appliances. Even though some DC appliances have long been available, their costs remain higher than AC ones mainly due to the economies of scale of manufacture of the latter [25]; [26].

Reports [27]; [28]; [29] and [30] indicated strong dissemination possibilities of AC (Alternate current) mini grids. Latest estimate indicates that about 40 percent of the required electricity access in
the off-grid regions should come from mini grids to achieve universal energy access by 2030 [1]. It is anticipated that with the consistent cost reduction of PV components, favourable global and national policy frameworks, effective financing initiatives and public-private integration in business delivery strategies would enhance this process [5],[28].

Development partners have funded thousands of mini grids to be deployed in several African countries [31],[32]. Many of the Sub-Saharan (i.e., Kenya, Ghana, Nigeria, Sierra Leone, Uganda, Tanzania), and South and South East Asian countries (i.e., Bangladesh, Myanmar, Cambodia, India, Vietnam) already developed geospatial plans and regulatory frameworks to support private sector into mini grid development and operation [33].

3. Approaches to delivery of universal electricity access

The ‘Energy for Development’ (e4D) programme carries out research in the wider areas of energy access at different Tiers of electrification (1-5) based on PV technology [34]. Research areas include solar home systems (SHS) and PV mini grids in both AC and DC with a range of attributes in suitability, modularity, reliability, efficiency, capacity expansion and productive use (Figure 1). The e4D research extends beyond the technological aspects to the value chain related to socio-economic development. This includes, needs assessment, stakeholder engagement and capacity building at local and national levels. Different approaches are applied for conducting research in the areas of energy access. These are: (i) system design and project delivery, (ii) data collection through structured interviews and focus group discussions, (iii) laboratory-based testing of appliances, (iv) primary and secondary data analysis and (v) field deployment of PV mini grids.

4. Results and discussion

4.1. Solar Home Systems

Here we present laboratory research undertaken as part of the e4D programme to support appliance quality, covering DC refrigerator and LED bulbs.

4.1.1. DC refrigerator: A DC refrigerator (rated voltage 12V/24V, total input power 48W, and rated current 4A/2A) was tested in the laboratory using an environment chamber (Figure 2) to simulate real life field ambient temperature and automated door opening was also performed. Performance of the refrigerator was tested at various internal thermal loads. Refrigerator pulldown and steady state
characteristics were analysed and finally the CoP (coefficient of performance) was calculated as 1.61. The refrigerator showed a soft start even for a very high thermal load (689Wh) (Figure 2). Such load was created with a combination of 30°C initial internal temperature (44x500ml water bottles as hot load), 3°C target temperature, 30°C ambient temperature (environment chamber) (Figure 3). A soft start characteristic is crucial for longevity of the battery of the solar home system.

4.1.2. **LED bulbs**: Nine LED bulbs (1-9W range) available in East African markets were tested to identify their quality. A 0.5m diameter integrating sphere (LabSphere®, Figure 4) was used to carry out the performance characteristics of the LEDs. These are, (i) luminous to radiant flux ratio, (ii) luminous efficiency and (iii) radiant flux as the efficiency of the LED bulbs. After an initial ‘0-hour test’ of nine samples, four LEDs were selected for ‘800-hour test’ to identify any significant changes in performance. Both ‘0-hour’ and ‘800-hour’ tests were performed at different controlled voltage levels (13.5V, 12.5V, 11.5V and 10.5V) to ascertain the performance of LEDs under various depths of battery discharge of SHS. Results in Figure 5, indicate that supply voltage levels between 13.5V and 10.5V have no significant effect on the performance of the LEDs tested. Two samples (S8 and S9) were below the manufacturers’ standards and three samples (S3, S4 and S5) outperformed the stated manufacturer standard thresholds in all three experimental indices. In the ‘800-hour’ test, which refers to about 5.5 months of usages of an LED bulb in off-grid setup, it was observed that out of four selected samples (S2, S4, S5 and S6) only one sample (S6) turned out as resilient to efficiency loss over the time (Figure 5).

**Figure 4.** Use of an Integrated LabSphere® for LED Efficiency testing in the e4D laboratory (left). LED samples and ‘800-hour’ test preparation of selected samples (right)

**Figure 5.** The Luminous flux to Radiant flux ratio for the ‘0-hr test’ for all nine samples (left) and the ‘800-hour test’ for selected four samples (right) at different levels of voltage supply.

4.2. **Direct Current (DC) mini grids**

As mentioned in Section 2, DC mini grids with DC appliances may have some benefits over the AC mini grids. The research here addressed two key areas: (i) techno-economic comparison of DC mini grid with AC counterpart, and (ii) suitable applications of DC mini grid. Results of techno-economic analysis indicate the suitability of DC mini grid based electrification approach can be cost competitive to AC mini grids. To deliver equivalent level of services, a DC mini grid is required to serve smaller load compared to AC mini grid. Table 1 presents daily electrical demand scenario in DC and AC in a Ugandan village and depicts the characteristics of such loads to determine the mini grid system size.
Table 1. Ugandan village daily electrical demand used to determine mini grid system size/architecture.

| Type of mini grid | Daily average demand (kWh/d) | Peak load (kW) | Load factor |
|-------------------|------------------------------|----------------|-------------|
| DC                | 15.54                        | 2.95           | 0.22        |
| AC                | 16.58                        | 3.04           | 0.23        |

To have an understanding of DC mini grid diffusion possibilities, anchor loads were considered, and further analysis undertaken. Table 2 shows the results of levelised cost of electricity for the village in Uganda. Regardless of load combination (with or without anchor load), DC mini grid represents cheaper LCOE and on average it can deliver electricity 19.5% cheaper compared to an equivalent AC mini grid.

Table 2. Levelised cost of electricity (LCOE) comparison for DC and AC mini grid.

| Min grid type | Load type          | LCOE      | Comment                                           |
|---------------|--------------------|-----------|---------------------------------------------------|
| DC            | Without anchor load| 0.62 USD  | DCMG represents 19.5% cheaper LCOE on average.    |
|               | With anchor load   | 0.54 USD  |                                                   |
| AC            | Without anchor load| 0.75 USD  | cheaper LCOE on average.                          |
|               | With anchor load   | 0.69 USD  |                                                   |

Considering the low voltage (24V – 48V DC) electricity distribution options from PV-battery DC mini grids in remote rural settings, and findings of techno-economic analyses carried out across various applications for suitability of DC mini grids, we conclude that such mini grids are appropriate in small geographic footprints such as small rural trading centres, remote settlements that are densely populated, rural health centres, off-grid lodges, small scale food and agro processing (water pumping, milling, milk chilling) and refugee camps.

4.3. AC mini grid research

A series of five PV mini grids were installed in East Africa between 2012 and 2016 with broadly the same design, encompassing a canopy (to hold PV modules) on top of shipping containers; the basic parameters are listed in Table 3. The mini grid was designed to provide single-phase AC electrification to the businesses in the trading centre, health centre and school. The areas around the intervention and control trading centres were surveyed two years prior and two years after the construction of a mini grid in the intervention trading centre. The process of engagement with the local communities, subsequent design, implementation, operation are covered in detail in Bahaj et al. [35], [36]. It is interesting to note

Table 3. Comparison of the Energy for Development Programme (e4D) East African mini grids.

| Trading Centre Name | Kitonyoni | Oloika | Shompole | Kanyegaramire | Kyamugarura |
|---------------------|-----------|--------|----------|---------------|-------------|
| Location            | Kenya     | Kenya  | Kenya    | Uganda        | Uganda      |
| Year installed      | 2012      | 2015   | 2015     | 2015          | 2015        |
| Design demand (kWh) | 28        | 28     | 17       | 28            | 28          |
| PV Capacity (kW)    | 13.5      | 13.5   | 8.4      | 13.5          | 13.5        |
| Battery Capacity (kW) | 38.4  | 38.4   | 38.4     | 38.4          | 38.4        |
| Gen. Capacity (kVA) | 12        | N/A    | N/A      | N/A           | N/A         |
| Inverter capacity (kVA) | 2×10 | 2×5    | 1×5      | 2×5           | 2×5         |
| Tariff (USD/kWh)1   | 0.7       | 0.7    | 0.7      | 0.07          | 0.07        |
| County/District GDP/capita (USD)2 | 417    | 1466   | 1466     | 137           | 137         |
| Affordability ratio (GDP/capita/tariff) | 600    | 2090   | 2090     | 1960          | 1960        |
| Daily demand growth rate (% design/annum) | 5.9    | 29     | 17       | 48            | 42          |

1. Kenya mini grids able to charge cost-reflective tariff, Uganda mini grids use national tariff
2. Kenya 2013 data from [37], Uganda 2014 data from [38].
from Table 3 that the observed growth in daily energy demand has varied considerably between the sites. The growth rate between plants sites shows an association with what is defined as ‘affordability ratio’, given by the sub-national GDP per capita divided by the kWh tariff charged by the mini grid. Nevertheless, there are still differences between the Kenya and Uganda sites, which may be due, in part to variations in the indirect measurement of GDP/capita (based on remote sensing of street lights) and other more complex socioeconomic factors such as local economy and approach to entrepreneurship and financial risk. Further analysis of the variation of consumption can be found in [35].

5. Conclusions

Solar Home Systems will play a crucial role towards ‘universal electricity access 2030’. The results presented here for two common SHS appliances, highlight a mixed quality standard. Although the DC refrigerator performed well, most of LED samples performed below the expected standard at the ageing test. In case of DC mini grids for universal electrification, the work shows that this may contribute to limited applications based on required load types and load concentration. For DC mini grids, in order to take advantage of inexpensive components, it is recommended to use low voltage distribution (24VDC – 48VDC).

The e4D AC PV mini grid interventions in Kenya and Uganda demonstrate that mini grids not only have the ability to invigorate rural communities by enhancing education and health provisions, but also enhance the local economy by creating growth in existing businesses and opportunity for establishing new ones. Having the present momentum in mini grid expansion across SSA, the e4D programme has extended its research in this field. A new phase of work [48] investigates mini grid networks in various modes: (i) clustered mini grids working as an independent grid, and (ii) mini grids connected to utility grids.

In summary, considering all the findings presented here, the following represent some policy implications to support electricity access:

(a) Off-grid electricity access projects should be area-specific based on required extent of distribution, load types and socio-economic conditions.
(b) Quality assurance of SHS components and appliances needs to be addressed as a matter of urgency to prevent loss of confidence in SHS systems in general.
(c) For loads densely concentrated in small geographical areas, applications of DC mini grids can be considered.
(d) The observed growth of demand in AC mini grids is sensitive both to the tariff set for electricity and to the economic conditions in the locality.

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