Impact of New Electric Cooking Appliances on the Low Voltage Distribution Network and Off-Grid Solar Microgrids

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Report Summary

Over three billion people around the world rely on biomass as their primary source of cooking fuel, a practise which is particularly prevalent across countries in Sub-Saharan Africa, Developing Asia, and Latin America. Cooking with biomass has significant negative health impacts, due to the toxic fumes produced which are estimated to cause over four million premature deaths annually. In addition, it negatively impacts the environment, through contributing to deforestation and climate change, which is exacerbated by increasing demand for biomass due to rapid population growth in these regions. Women and girls are disproportionately affected by these impacts as they are often responsible for cooking and the collection of cooking fuels. Increased adoption of electricity as a replacement for biomass as a source of cooking energy is one potential solution to reduce these negative environmental and social impacts.

The studies presented in this report identify the main technical challenges associated with accommodating electric cooking on microgrids and low voltage (LV) distribution networks in sub-Saharan Africa. Evidence and experience has shown that the adoption of electric cooking appliances can already be supported by some networks without the need for any upgrades in the system. This is primarily within networks which have been overdesigned relative to existing electrical demand and as a result, sufficient headroom to adopt clean electric cooking appliances exists. Simultaneously, where system designs more closely match baseload (non-cooking) characteristics, limitations may occur when supporting the addition of electric cooking loads. Identifying these limitations has been the subject of investigations in this report.

The technical analysis was primarily supported by models developed in OpenDSS. Load flows, voltage profiles and transformer/power inverter requirements were modelled to investigate the performance of representative LV and microgrid network topologies before and after the introduction of loads from different sized electric cooking devices. This research was conducted as a part of the MECS (Modern Energy Cooking Solution) consortium.

The main findings are:

LV network (findings summarised in Table 1 below)

- LV networks (assuming sufficient electricity generation exists) have a strong capability to support electric cooking loads without exceeding substation capacity and voltage drop constraints, and can already support cooking appliances at low power ratings (e.g. 300W rice cookers) for 100% of users connected under the same substation.
- LV networks are also capable of supporting the addition of some medium powered electric cooking devices. Up to 45% of households connected to the same secondary substation can be equipped with 1kW Electric Pressure Cookers (EPCs) without breaching network constraints, whereas 600W EPCs can be supported for up to 75% of households.
- Introducing a larger number of EPCs or higher-powered devices without any mitigation methods increases the risk of exceeding the maximum power capabilities of the local distribution transformer.

Table 1. Electric Cooking within LV Network – Summary Table

Scenario	**At 100% eCook penetration ✓ within constraints ✗ exceeds limits**		**Comment Approx. viable eCook penetration (within voltage and power constraints)**
	Voltage	Power	
300W Rice Cookers	✓	✓	100% adoption can be supported
600W EPC	✓	✗	75% adoption can be supported
1kW EPC	✓	✗	45% adoption can be supported. Voltage drops at network extremities approach limits

Off-grid solar microgrid

- Some off-grid solar microgrids, despite being primarily designed to provide basic access to electricity (Tier 1,2 and 3 according to ESMAP [1]), already show sufficient amount of power capacity to support some adoption of eCook appliances. This is a result of solar microgrids being 'overdesigned' for the existing demand or other microgrids (e.g. hydro-based microgrids) having an abundant power source.
- Where there is insufficient generation capacity, (in addition to the other considerations below) upgrading systems to support eCook loads in microgrids can be achieved by installing an additional power inverter in parallel to pre-existing (together with up-scaled PV array) or by adoption of a back-up generator supporting high cooking loads.
- Studies performed suggest that existing microgrid cables can provide efficient power distribution for all modelled scenarios up to and including 100% penetration of 1kW EPCs.

Other considerations

- One of the main challenges associated with accommodating cooking loads is that cooking routines often coincide with peaks in non-cooking electrical demand. Spreading cooking demand over time could also enable higher penetration of users with electric cooking appliances.
- The ability to support increased levels of adoption and/or higher-powered electric cooking devices by the systems analysed in this report could also be improved by implementing Active Network and Demand Side Management.

Contents

1. Introduction

The key objective of this report is to present studies carried out by the University of Strathclyde relating to the adoption of clean electric cooking devices on two types of electrical system infrastructures in sub-Saharan Africa. These are summarised as:

1. **Low voltage (LV) distribution networks (downstream of secondary substations):** The LV network models generated to conduct the necessary eCook penetration studies for this report were primarily based on literature outlining design guidance, standards and practices, with input from a Power System Planning Engineer from the Electricity Supply Corporation of Malawi (ESCOM). The results of studies on the impact of adoption of different eCook devices on LV distribution networks is provided in Section 2.

2. **Rural off-grid microgrids with centralised generation and storage:** The microgrid network models were designed using data available from Powergen microgrids in Kenya and Tanzania. The parameters selected for the microgrid were based on publications provided by Powergen, the incumbent utility grid operator. Analysis of electric cooking impact on the rural off-grid microgrids is presented in Section 3 of the report.

Power systems models have been developed using OpenDSS for both types of electrical infrastructure. Based on observations made from study outputs, the main technical challenges associated with eCook deployment in these contexts were identified and are described in Section 2 and 3. The report also considers potential implementation strategies and interventions which may be required to accommodate 'significant' levels of electric cooking deployments on such networks (see Section 4).

1.1. Methodology Applied to Perform Technical Network Studies

The tools to support network studies presented in this report were developed to give understanding of the principal technical challenges associated with adoption of electric cooking on existing networks in sub-Saharan Africa. The outcomes illustrate load flows across investigated networks before and after adoption of eCook devices, voltage profile distribution within each system as well as requirements on the transformer/power inverter. The models can be readjusted according to users' requirements and can thus be used for further analysis in the future.

To perform network analysis, sets of input data must be specified. For this study the OpenDSS[1] Engine was used to compile sets of output data, as specified according to Figure 1-1 below. The diagram presented is valid for the LV network model as well as for the microgrid system.

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[1] https://sourceforge.net/p/electricdss/wiki/Home/

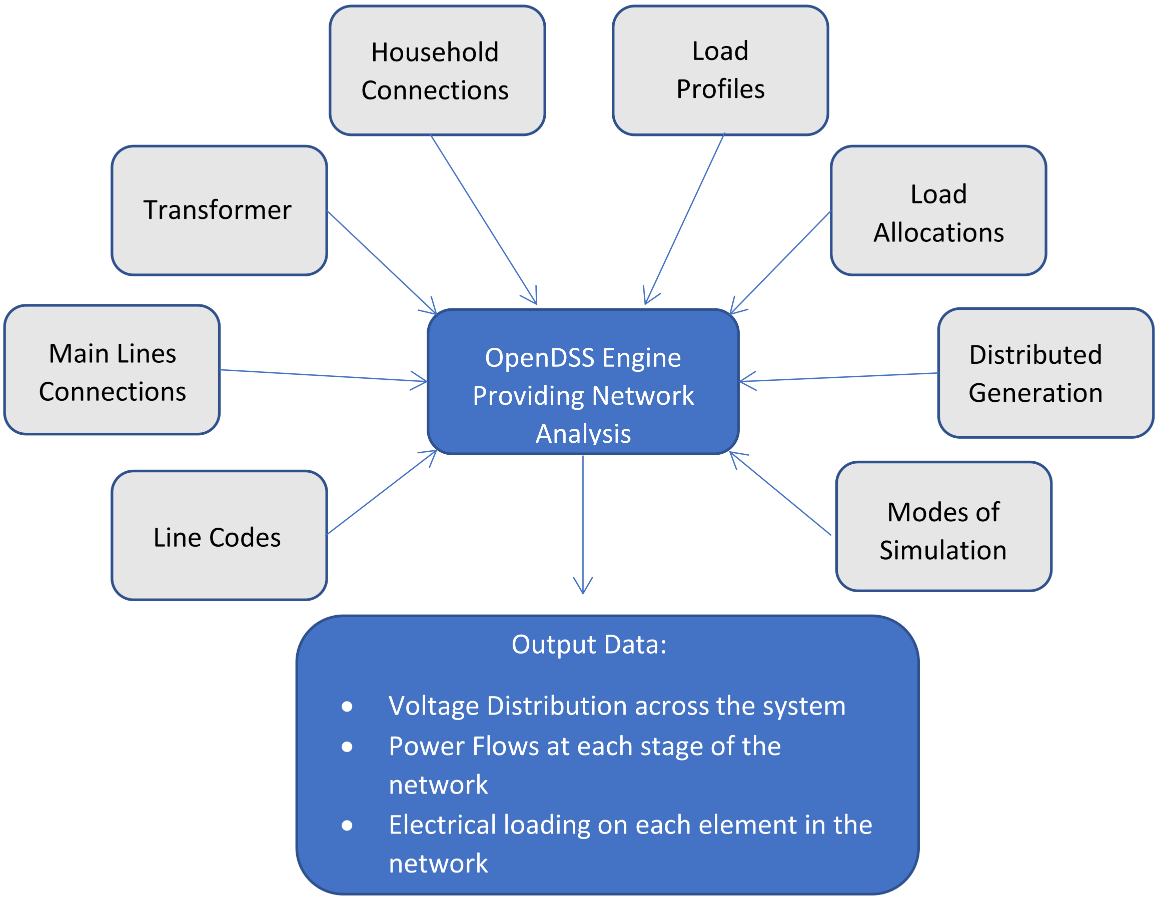

Figure 1-1. Network Modelling Data Flow

A brief description of each of the input data groups used to generate network analysis is presented below:

1. Line Codes – file storing parameters of the cables used in the network model.
2. Main Lines Connections – file illustrating connection between busbars in the network.
3. Transformer – file storing the main parameters of a power transformer supplying LV network.
4. Household Connections – files including information on household connections and phases.
5. Load Profiles – excel file presenting 24-hour household load profiles with 1-minute resolution. It gives understanding on daily system dynamics.
6. Load Allocations – file allocating Excel load profile to households represented in the network model.
7. Distributed Generation – file allowing introduction of distributed generation at any location of the network. It also gives capability to define generation profiles to simulate impact on the network.
8. Modes of Simulation – defines time resolution to run the simulation.

More information about OpenDSS network models are to be specified in the User Guide which gives understanding on how the network could be readjusted to perform studies for different topologies. Models will be shared on the University of Strathclyde Energy for Development website[2] in November 2020.

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[2] https://strath-e4d.com/

2. LV Network Studies

The first section of this research presents the impact of electric cooking on available LV network infrastructure as well as potential implications on the power system which may be caused. A diagram presenting an example of a LV network is shown in the Figure 2-1.

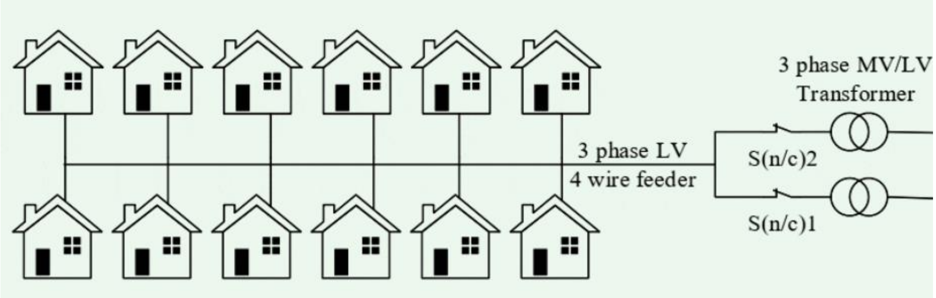

Figure 2-1. Example of a LV Distribution Network Arrangement

The LV network used for analysis is energised through a substation which steps down the voltage to 220V (single-phase) and 380V (three-phase) at 50 Hz which is in the most common LV system configuration across Sub-Saharan Africa. Operationally, the rating of the transformer is selected based on estimated power consumption within houses connected to the same substation. The transformer capacity depends on the total After Diversity Maximum Demand (ADMD) parameter (forecasting 15-20 year demand growth) which can vary depending on different types of customers consuming electricity, connected downstream from the substation [2]. Through the analysis of various LV networks in developing countries, the number of customers and the size of transformers were used to estimate “typical” ADMD parameters for further LV network modelling work presented in this report. Specifically, based on the analysis of several LV network networks located in India, the ADMD for the network investigations in this study was set at 500W [3]. While it would be preferable to have equivalent data from sub-Saharan Africa grids to support this assessment, no appropriate source was available at the time of writing.

The sizing of the distribution network is another aspect considered in the research. This will have a crucial impact on analysis of the voltage profiles at different stages of the system, especially after the connection of cooking appliances which may require high power to be delivered. As a result, the maximum voltage drop allowed by the network providers could be exceeded, meaning that the overall power distribution efficiency can be low. To represent a generic model of the LV distribution system, Aerial-Bundle Cable (ABC) with a cross-sectional area of 50mm^2 was selected as this is typically used for LV network design in various countries across sub-Saharan Africa [4], [5]. Occasionally, in areas of low power consumption and relatively short distances from the substation, 35mm^2 ABC cable can be used to reduce system expenditure costs.

To estimate the number of households connected downstream from the secondary transformer, five different villages were analysed with respect to their population as well as the number and rating of transformers installed [3]. It was found that a single substation provides electricity to a minimum of 21 and maximum of 111 households. The recommended distance from the substation should be lower than 500 metres [6].

2.1. Demand Specification

Having basic specification for the network models, it is important to introduce electricity demand for each household connected since it will have a direct impact on the performance of the system. To do so, five different household categories of users were selected, according to Mandelli [7]. These represent different categories depending on types of appliances, their power ratings, quantities, etc.

The variations between demand typically depends on the family status and is often correlated with the capabilities to afford electrical appliances. The full list of users' demand profiles is presented in the tables 2-6.

Once demand was specified, load profiles were generated using LoadProGen[3][4] (a tool building up realistic estimation of the electric load profile) with the default settings according to [6].

Table 2. Appliances within Category 1 Household.

Appliances	Power Consumption (Watts/appliance)	Quantity
Lights	3	4
Phone Charger	5	2
Security Lights	5	1
Average Daily Energy Consumption (Wh/day)	335	

Table 3. Appliances within Category 2 Household

Appliances	Power Consumption (Watts/appliance)	Quantity
Lights	3	4
Phone Charger	5	2
Security Lights	5	1
Radio	5	1
AC TV	100	1
Average Daily Energy Consumption (Wh/day)	689	

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[3] https://daneshyari.com/en/article/1046813

[4] Household demand profiles used to verify models were developed with the support of Dr. Chris Mullen at the University of Newcastle.

Table 4. Appliances within Category 3 Household.

Appliances	Power Consumption (Watts/appliance)	Quantity
Lights	3	8
Phone Charger	5	2
Security Lights	5	2
Radio	5	1
AC TV	100	1
Fridge (small)	250	1
Average Daily Energy Consumption (Wh/day)	2770	

Table 5. Appliances within Category 4 Household.

Appliances	Power Consumption (Watts/appliance)	Quantity
Lights	3	12
Phone Charger	5	4
Security Lights	5	4
Radio	5	1
AC TV (small)	100	1
Fridge (small)	250	1
Internet Router	20	1
Laptop	55	1
Standing Fan	55	1
Decoder	15	1
Average Daily Energy Consumption (Wh/day)	3165	

Table 6. Appliances within Category 5 Household.

Appliances	Power Consumption (Watts/appliance)	Quantity
Lights	3	16
Phone Charger	5	4
Security Lights	5	6
Radio	5	2
AC TV (big)	200	1
Fridge (big)	400	1
Internet Router	20	1
Laptop (big)	80	2
Decoder	15	1
Standing Fan	55	2
Average Daily Energy Consumption (Wh/day)	6142	

The average daily power consumption as well as cumulative energy usage of each user category is presented in the Figure 2-2 and 2-3 respectively.

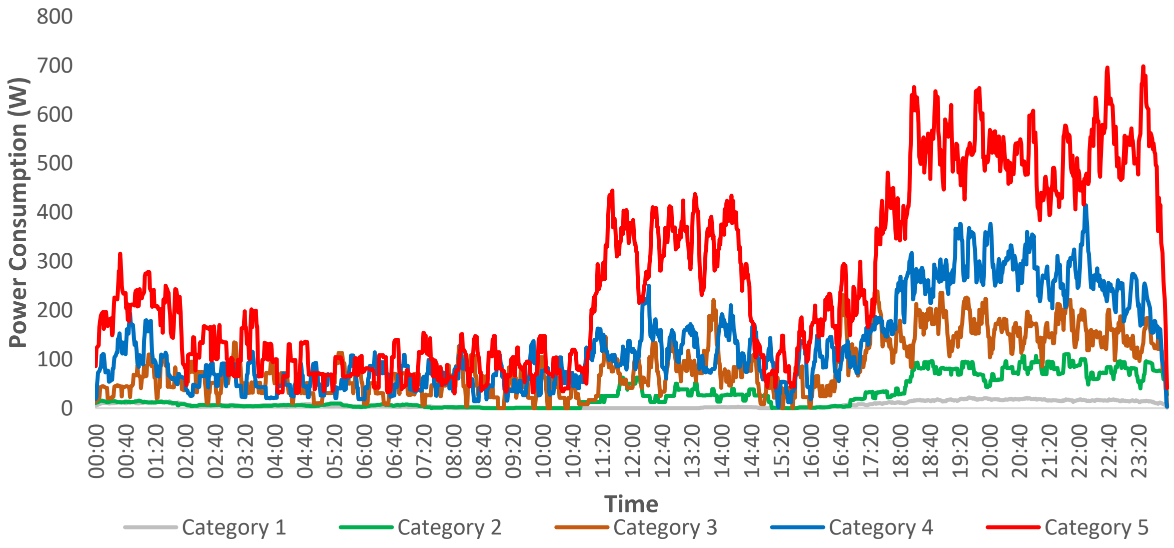

Figure 2-2. Average Demand for Household in the Network per each Category

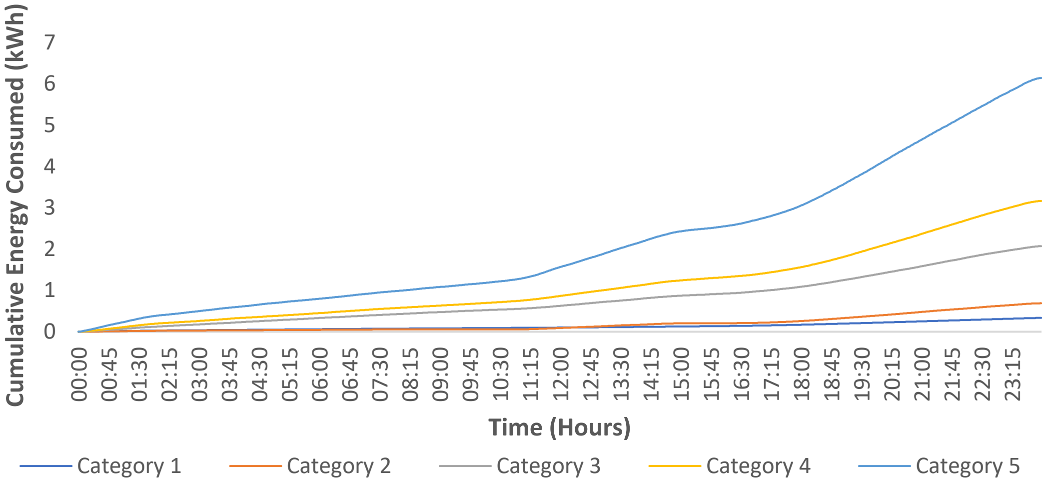

Figure 2-3. Cumulative Daily Energy Consumption for each Household Category

It is clear from Figure 2-3 that the load profiles generated provide demand diversification between different types of users. It is apparent that peak power consumption for Category 5 households is approximately 20 times higher than that for Category 1 households. The variations might depend on the overall ability to pay for electrical appliances presented to end customers, types of businesses operating, number of consumers per household and more.

Network studies considered in this report represent a mix of users from each of Categories 1 to 5 which implies that the system represents a semi-urban or urban context where customers can reach high energy tiers. Rural on-grid energy access end customers would normally make use of lighting systems, phone charging and sometimes TVs. Occasionally, some people would make use of a refrigeration system [8].

2.2 LV Network Topology

Based on LV network parameters specified in this report, an appropriate topology has been developed to represent the performance of a “typical” LV network deployed in sub-Saharan Africa before and after installation of electric cooking appliances. The topography was developed with support from ESCOM power engineer currently enrolled in research at the University of Strathclyde as well as literature review giving basic understanding on LV network characteristics in sub-Saharan Africa [9].

The secondary transformer of the network supplies four feeders with 17 to 22 households connected to each. The service lines between busbars and households were modelled to be 20 metres long (according to the network design files listed in the previous sections). Each of the households was energised based on a single-phase connection from one of the three-phase circuits (red, blue and yellow).

The topography of the LV network analysed is presented in the Figure 2-4.

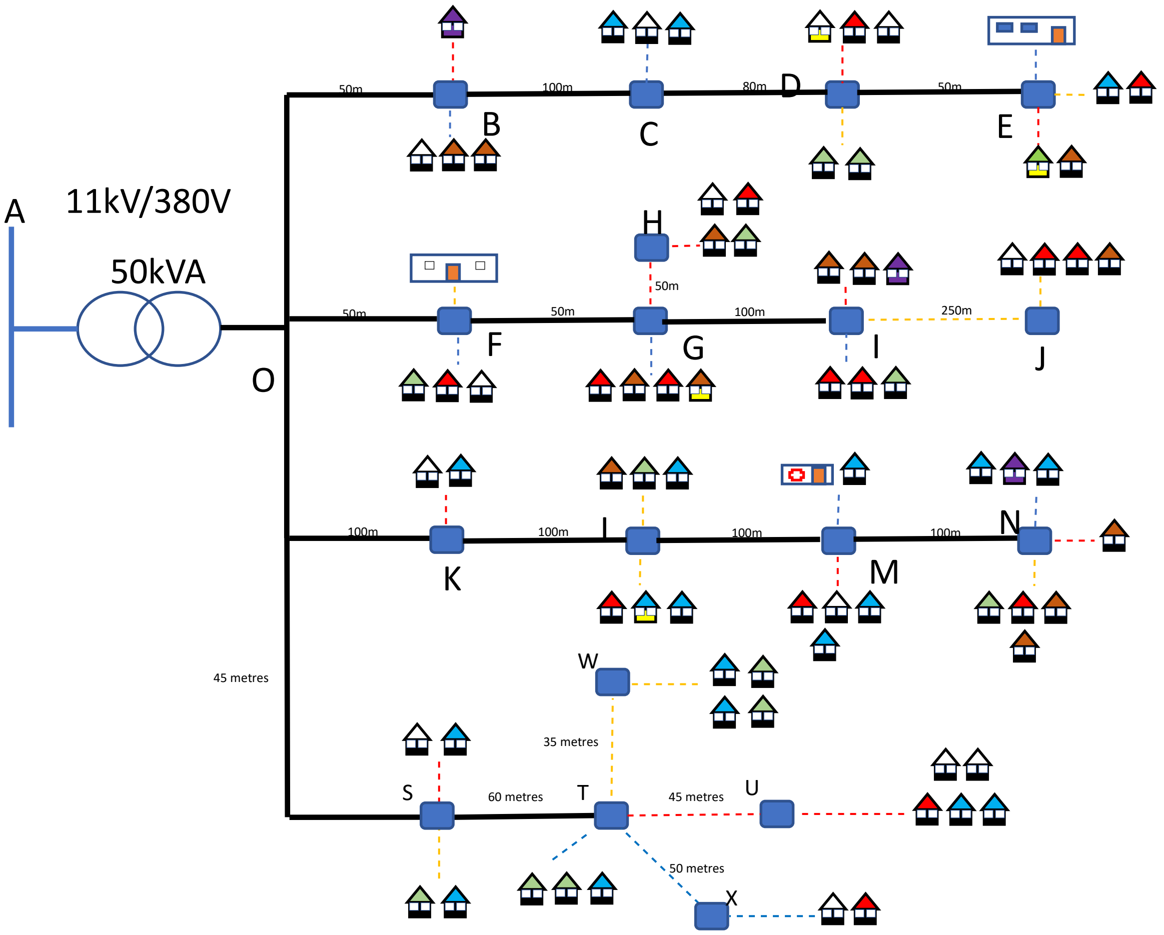

Figure 2-4. LV Network Topography

The colours of the icons represent the category of the user; white rooftop- category 1, green – category 2, brown – category 3, blue – category 4 and red – category 5. Additionally, yellow house blocks represent mobile money services whereas purple indicates barber shops. The other icons connected to busbars E, F and M represent a school, an enterprise, and a pharmacy respectively, as specified by Mandelli [7]. The positions of the households were allocated randomly. Allocating households with higher demand closer to the transformer circuit will provide a better performance of the system due to shorter distance require for power distribution. Allocating households with high demand further from the substation raises risk of higher voltage drops along the distribution cable which may introduce additional network losses as well as it can reduce power consumption of the electric cooking appliances.

With the network specification in place, the size of the transformer established and the ability for different non-cooking demand specifications to be characterised, a LV network model was developed and populated for use in OpenDSS. This model formed the basis for the subsequent LV network studies involving eCook in the remainder of the report. The topography for the scenario investigated is presented in Figure 2-5 where each of the busbars correspond to those in Figure 2-4. The red triangle represents the position of the substation in the central location of the network.

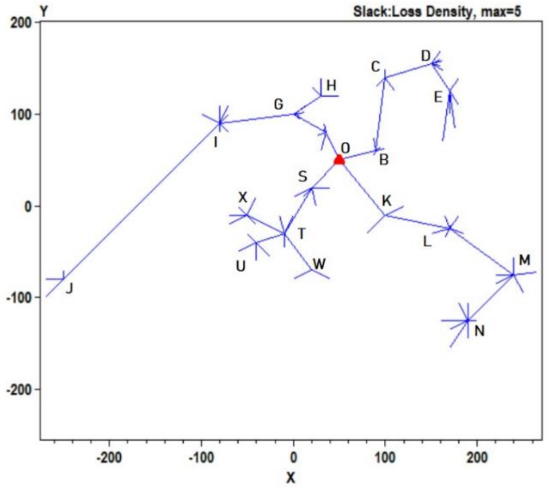

Figure 2-5. LV Network OpenDSS Topology

The model was used to perform a series of studies to illustrate the dynamics of the LV network before and after the introduction of eCook to highlight the issues which new cooking demand may cause within the system. This is captured in the following sections.

The summary of assumptions used to develop the LV network model is presented in the Table 7 below.

Table 7. LV Network Design Assumptions

Total Number of Households Connected	79
Number of Category 1 Households	13
Number of Category 2 Households	13
Number of Category 3 Households	13
Number of Category 4 Households	19
Number of Category 5 Households	15
Other Households (including businesses, school, etc.)	6
Substation Capacity	50 kVA
Number of Feeders from the Substation	4
Number of Households per Feeder	Between 17 and 22
Distribution Cable	50mm^2 ABC Cable

2.3 Pre-eCook Network Analysis

The first simulation performed considers voltage variations at each household in the network with a demand of 500W per household. This presents a critical condition at which transformer operates close to its maximum rating.

According to the network design specification, the maximum permitted voltage drop at the LV network typically should not exceed 5% between the secondary substation and the customer [10]. Connecting loads of higher power ratings than specified by the Distribution Network Operator (DNO) at the design stage (especially electric motors) can cause significant voltage drops at the distribution network which can indicate that network experiences high losses and replacement of cables may be required [11].

The voltage profiles under defined scenarios for the LV network developed are presented in Figure 2-6 where 1pu represents rated voltage of 220V. Busbars of the ultimate sections of each feeder are labelled. Bottom red line set at 0.95pu presents minimum voltage acceptable by the DNO.

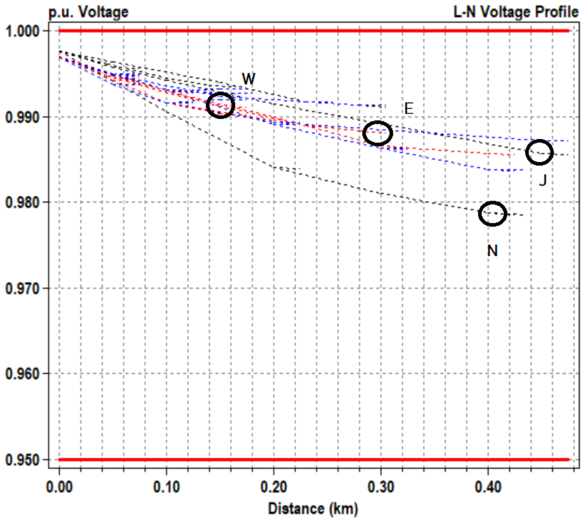

Figure 2-6. Network Voltage Levels under the load of 500W at each Household

From Figure 2-6, a typical voltage drop between substation and end-customer in the considered scenario is approximately 1-1.5% with the maximum of 2.1% within one of the phases at busbar N. The analysis illustrates that, under the specified conditions, the voltage is within the recommended limit of 5%. It is also observed that in the busbar nodes furthest away from the transformer station the voltage drops are higher. This is due to the long distance for which the current needs to pass through the cable to reach the higher number of end customers.

As a result, supporting the adoption of eCook devices is expected to be most challenging in the 'end-portions' of the LV network where, depending on the size of voltage drops, customers may experience increased times for cooking. There are several possible solutions to this problem that have varying degrees of complexity and cost. For example, one way it could be addressed is by installing additional power converters at various points in the network to step up voltage to 220V at each household or through the addition of distributed generation with capabilities to boost voltage by injecting power to the network. In either case further studies would be needed to provide optimal operation of the electric cooking system on the network.

Load flow analysis at each feeder of the substation was also performed to understand whether LV networks operate below maximum thermal capacity limits for 50mm^2 ABC of 183A [12]. According to the studies performed, the maximum current within the whole distribution model reaches 24A, proving that under a pre-eCook scenario the network operates within acceptable conditions and without risk of exceeding maximum current ratings.

2.4. Pre-eCook Typical 24-hour Profiles

In the following section the temporal behaviour of the LV network across a 24-hour period, assuming 100% reliability of the system (no power outages) is considered for the pre-eCook loading configuration. This analysis is particularly important since it gives an understanding of voltage variations in the system across the whole day. It also indicates periods when the loading on the distribution transformer is high, and thus periods when the network is most vulnerable to the addition of increased loads from electric cooking and other new electrical devices.

The daily load profiles were matched with households according to the previously defined specification in Section 2.1. The transformer was set to operate as a slack bus modelled as a fixed voltage source. The overall power flows through the substation are illustrated in the Figure 2-7.

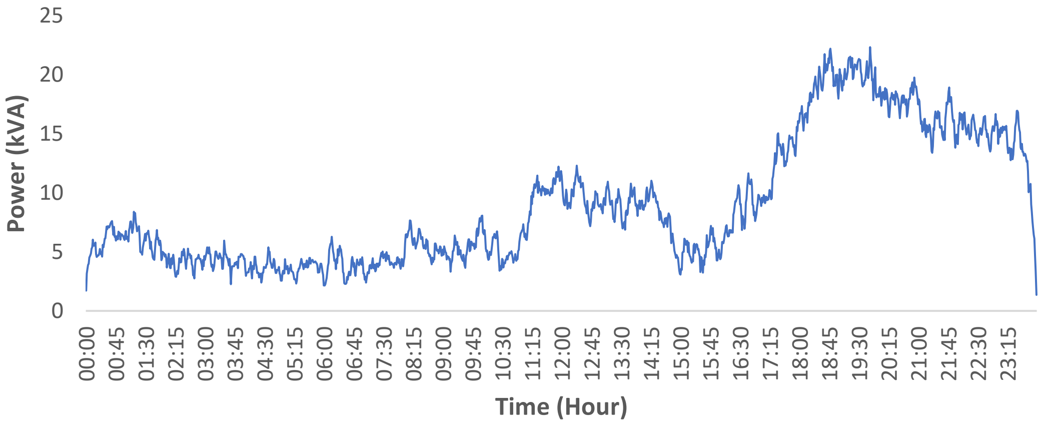

Figure 2-7. Power Flow through the Transformer under Pre-eCook Scenario

From these figures it was determined that the maximum peak power demand in the system occurs in the evening and reaches approximately 24kVA on a typical day. The second highest peak is experienced in the early afternoon. Both peaks can be easily met by the installed capacity of the transformer and the system can operate within safe conditions under the specified pre-eCook load demand.

The previous analysis presented in relation to voltage (see Figure 2-6) identifies that the highest voltage deviations are experienced in parts of the network feeders which are furthest away from the substation circuit, at busbars E, J, N and W. This section of the report illustrates a 24-hour voltage profile at each of these nodes under the pre-eCook scenario. The voltage profiles are presented in Figures 2-8, Figure 2-9, Figure *2*-10 and Figure 2-11.

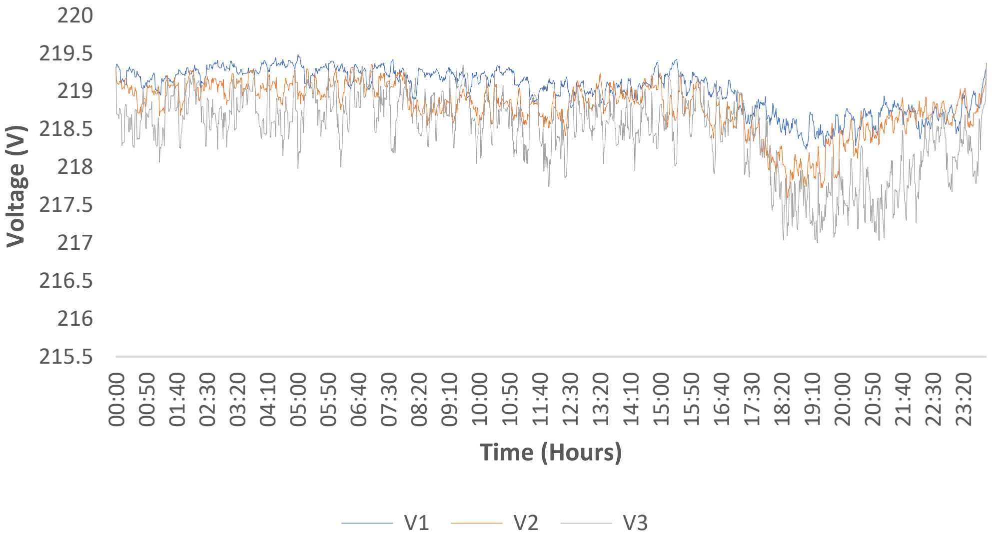

Figure 2-8. Voltage Profiles at Busbar E.

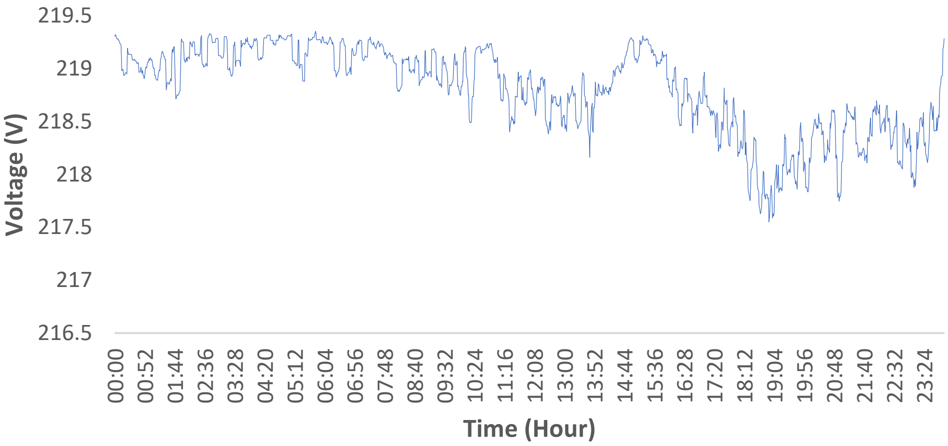

Figure 2-9. Voltage Profile at Busbar J (single-phase).

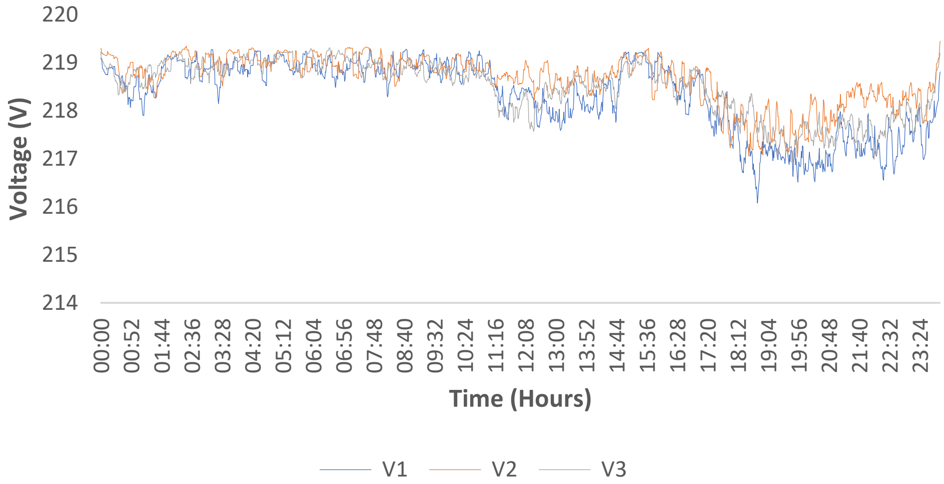

Figure 2-10. Voltage Profile at Busbar N.

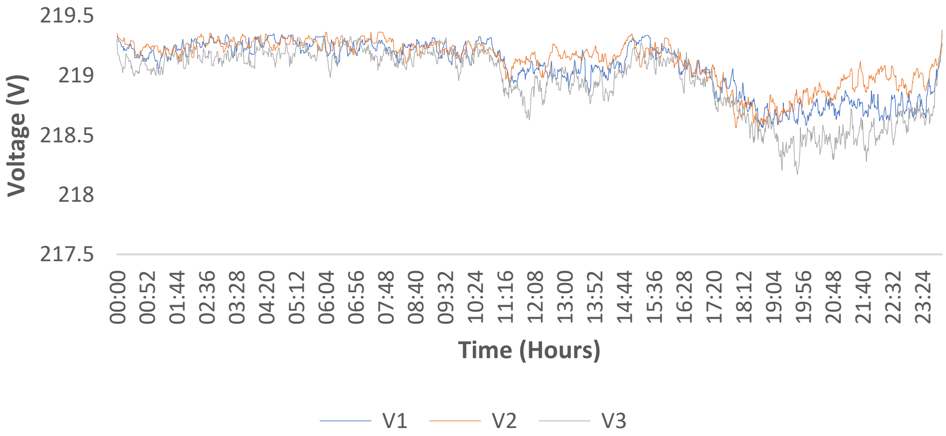

Figure 2-11. Voltage Profile at Busbar W.

The figures presented confirm that at each feeder voltage is maintained within acceptable limits for the full period of 24-hours. This is also the case during periods with the highest evening demand when the voltage remains high. In addition, voltage drops across some of the phases are higher than others, shown for example in node E's voltage profile (see Figure 2-8). This phenomenon is a result of a load imbalance within the system and is primarily driven by the connection of the small businesses (like the pharmacy or school as an example), making use of several high-power devices at the same time supplied by a single-phase system. This does not, however, pose a significant issue under the pre-eCook scenario considered.

2.5. Electric Cooking Demand Profiles Specification

In sections 2.3 and 2.4, the performance of the LV network has been presented under a scenario where no eCook systems have been deployed. The network in this case operates within safe voltage limits and without violating the maximum power constraints of the transformer.

The next section of this report investigates the performance of the network after connecting eCook devices. To do so, cooking demand profiles were created based on cooking diaries surveys conducted with a group of people currently relying on traditional sources of energy for cooking residing in the Northern Province of Rwanda. The studies were undertaken in August 2019 and are used as a baseline demand profile for the adoption of eCook systems. Users residing in Murambi village were asked to estimate the typical time for cooking. The results of the surveys are presented in Figure 2-12. It illustrates %-age of all Murambi residents cooking at the particular time of a day (currently on charcoal and wood). Field studies in Murambi also indicated that all users surveyed cook lunch (typically between 10am and 12.30pm) as well as dinner (between 5pm and 9.30pm).

Other demand profiles indicating typical time of cooking were developed by the researchers at University of Strathclyde, as outcome of field work conducted in Malawi in 2019 and are presented in Appendix A.

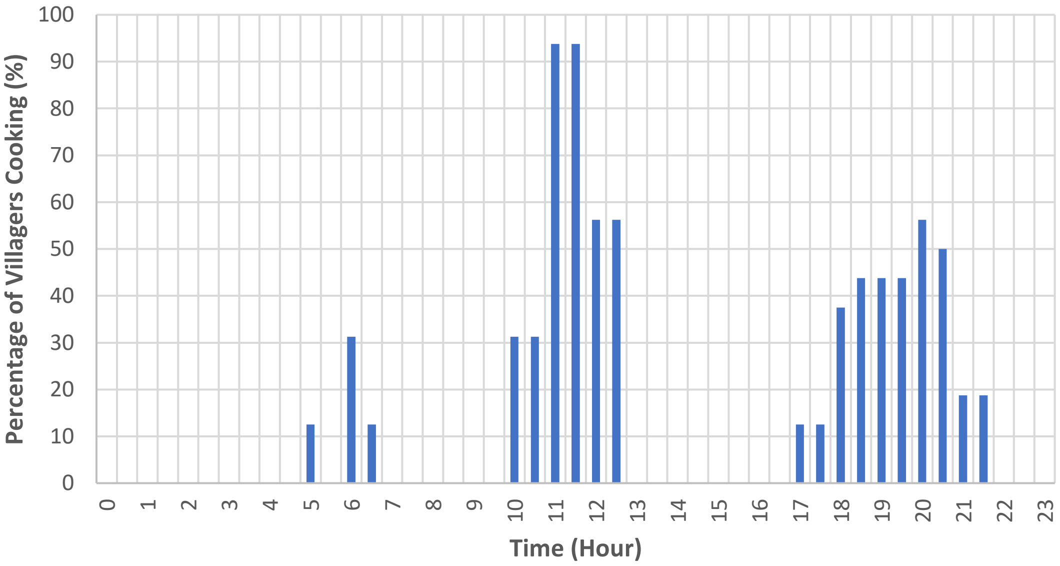

Figure 2-12. Cooking Patterns in Murambi Village, Northern Province of Rwanda

Figure 2-12 shows there are typically three periods when villagers cook; morning (between 5am and 6.30am), midday (between 10am and 12.30pm) and evening (between 5pm and 9.30pm). Figure

2-12 shows that between 11am and 12pm the highest proportion of villagers cook at the same time (approximately 93% of all Murambi residents). This indicates that during this period the highest power demand for eCook appliances can be expected. The second peak is observed at 8pm when 55% of all villagers cook. This suggests that evening peak cooking demand (in comparison to midday peak) might be significantly lower as evening cooking routines appear to be more diversified (spread over 4.5 hours in the evening in comparison with 2.5 hours at lunchtime).

Limitations of LV network studies

Analysis performed under Section 2.6 has been conducted based on estimated demand profiles for cooking, according to research conducted in Murambi village in Rwanda. Real (measured) electric cooking demand could be noticeably different due to the use of different cooking devices with different power requirements and efficiencies. Cooking durations were also indicated in 30 minute intervals in line with data and modelling requirements, while in practice a far more nuanced electrical demand is likely to be required. The introduction of detailed demand profiles for populations on LV networks is an important work area for future study and will provide a better understanding of the feasibility of adoption of electric cooking appliances within LV networks.

Further simplifications used in the LV network analysis are associated with cooking devices' performance characteristics. Some cooking devices (e.g. Electric Pressure Cookers (EPCs)) draw large amounts of energy in the first phase of operation, then stop consuming electricity until their temperature drops below a threshold when they start drawing power again. This cyclic operation means that for some portions of cooking routines power consumption is very low and the operational loading on the transformer might therefore be lower than modelled at various points. However, it is not recommended to try to exploit such fine margins when designing networks and upgrades given the impact of other variables such as non-cooking demand growth and broader networks fluctuations.

Finally, the analysis presented here considers only the LV network system, assuming that power systems do not experience any issues with maintaining voltage levels (due to, for example, ageing and inefficient transmission systems) and that they possess sufficient installed generation capacity to support increases in electrical demand from widespread adoption of electric cooking and/or other equivalent load growth which may become challenging in various countries across sub-Saharan Africa.

2.6. Impact on LV Network after introduction of Electric Cooking Appliances

To verify the impact of electric cooking appliances on the LV network, three different scenarios were simulated. Each aims to identify whether network constraints arise depending on types of cooking appliances introduced within each household, as specified below:

Scenario 1 – Introduction of 300W rice cookers

Scenario 2 – Introduction of 600W EPCs

Scenario 3 – Introduction of 1kW EPCs

The analysis performed illustrates the capabilities of the transformer to support power under each of the three cases. It also allows understanding of whether the distribution cables can maintain appropriate voltage levels. For each of the scenarios it is assumed that supply voltage is kept at rated 220V and transformer does not experience any voltage fluctuations caused at MV or HV level of the power system.

Based on the comparison of non-cooking profiles introduced in Section 2.1 and typical cooking routines in Murambi presented in Figure 2-12, it is observed that the high cooking demand can be expected at a similar time of the day as the non-cooking demand (between 11am-1pm and 6pm - 9pm). The combination of peak loads in this way across all the installed customers can introduce technical difficulties for the installed equipment (e.g. distribution transformer) and network operation if it becomes high enough.

To verify the feasibility of electric cooking on the LV network, the new cooking demand was equally distributed within all connected households and eCook power consumption for each household was scaled down by the percentage of cooking events across the whole village at each hour of a day, according to the data illustrated in Figure 2-12. It was also assumed that electric cooking appliances installed within each household are switched on for the whole duration of existing cooking events (according to Figure 2-12) where charcoal is currently the dominant fuel. As such, the reported scenarios do not incorporate actual cooking behaviours using the modelled cooking devices, and behavioural changes as a result of transitioning from biomass to electric cooking are not represented (e.g. improvements in cooking time, switching electrical appliances on and off, cooking cycles and so on).

Based on new load profiles obtained, further analysis illustrating eCook feasibility for each of three scenarios has been performed. Studies indicating impact of 300W on LV networks (Scenario 1) are presented under Section 2.6.1, whereas feasibility studies for adoption of 600W (Scenario 2) and 1kW (Scenario 3) EPCs under Sections 2.6.2. and 2.6.3. respectively.

2.6.1. Impact of 300W Rice Cookers on the LV Networks

The first scenario considers the impact of 300W electric rice cookers on LV network, assuming all households are equipped with these cooking appliances. The additional 'estimated' cooking demand was added to the baseload (non-cooking) demand to obtain final profile to be supplied by the transformer. The overall power demand estimation (blue) and transformer installed capacity (orange) for the whole LV network over the 24-hours period are presented in the Figure 2-13.

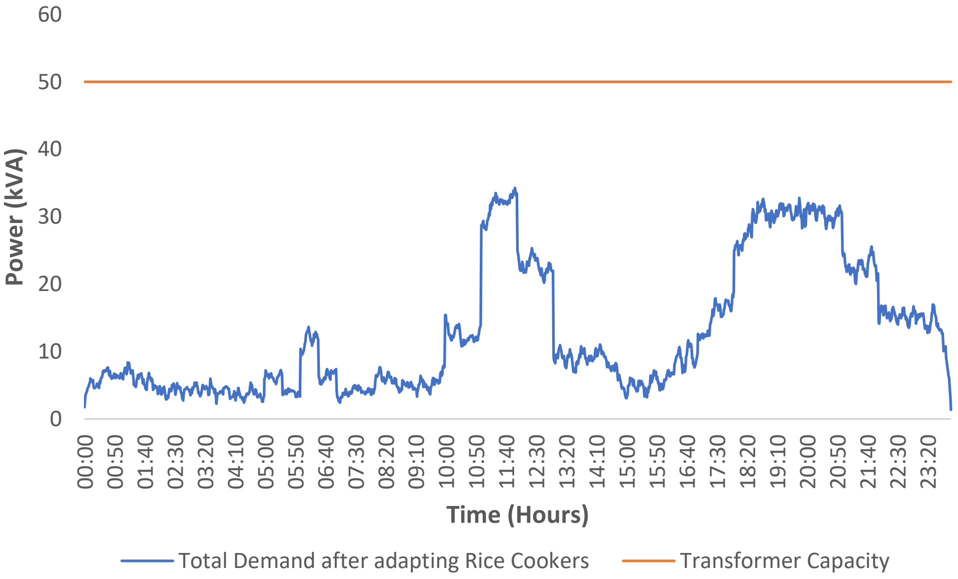

Figure 2-13. Transformer Load After Adoption of 300W Rice Cookers

Based on the estimated demand profiles including rice cookers it is observed that substation has sufficient installed capacity to support 100% of the users in this case. The voltage profile distribution across the whole LV network during the highest loading period (midday cooking) is presented in the Figure 2-14. Busbars W, E, J and N have been highlighted (see Figure 2.3) to show the nodes at each of the four feeders where highest voltage drops are expected.

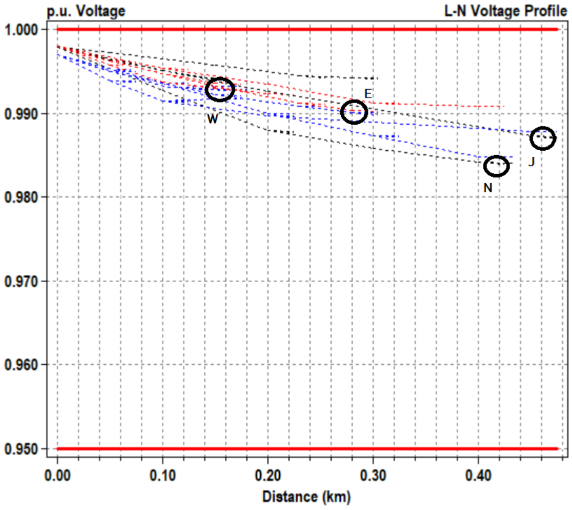

Figure 2-14. Voltage Distribution after adoption of 300W electric Rice Cookers within the LV Network

Figure 2-14 indicates that the voltage drop after the adoption of 300W electric rice cookers in each household connected under the same substation can be comfortably maintained within acceptable limits and regular performance of the network can be preserved.

2.6.2. Impact of 600W EPCs on the LV Network

The second scenario considers the adoption of 600W EPCs on the LV network by all households. Similar to the assessment performed under section 2.6.1, demand profiles were created based on results gathered from Murambi village, as presented in the Figure 2-12. The first evaluation performed considers the capability of the power transformer to provide electricity for a 600W EPC in every household. The 24-hour profile for power consumption is presented in the Figure 2-15 below.

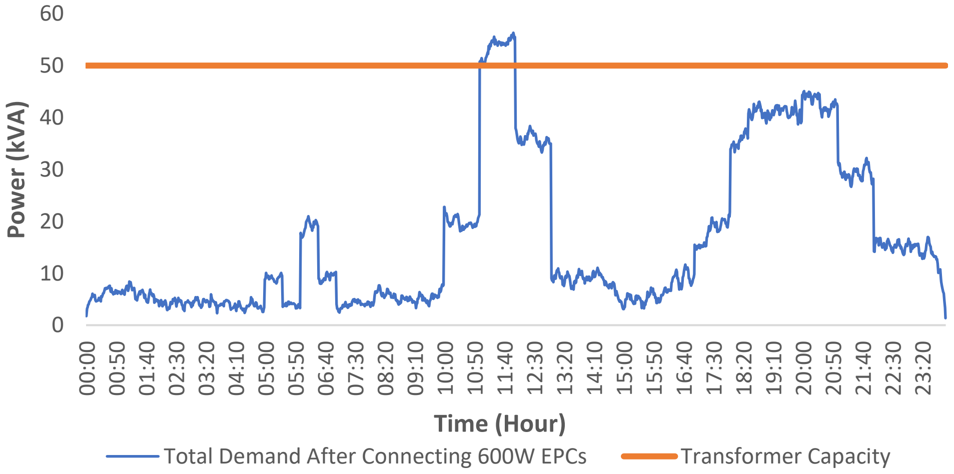

Figure 2-15. Power Consumption after Connecting 600W EPCs at each Household Level.

Based on Figure 2-15, if all households were to own an EPC, the new electric cooking demand would exceed the maximum power transfer capabilities provided by the 50kVA transformer. However, given the small magnitude of the breach (around 7kVA) it is concluded that network can safely support 600W EPCs for approximately 85% of all households, considering events when loading on the transformer is highest (at 12pm when peak cooking demand coincides with high baseload demand). Taking into account that 10% of capacity is held in 'reserve' on a transformer to accommodate load variations, it was concluded that maximum recommended penetration of 600W EPCs within LV network can reach 75%. Increasing the penetration of EPCs in the network could be supported by various Active Network Control concepts and/or Demand Side Management solutions which would need to be investigated as detailed in Section 4.

Further studies were conducted to assess the performance of the LV distribution cables under the installation of 600W EPCs to verify whether network operates efficiently. The analysis has been completed for 100kVA transformer circuit on the basis that the transformer was upgraded, or had originally been designed, to support additional loading (i.e. to remove the limitations of the 50kVA previously shown). The voltage distribution within the LV network during periods of peak power consumption is shown in the Figure 2-16 below.

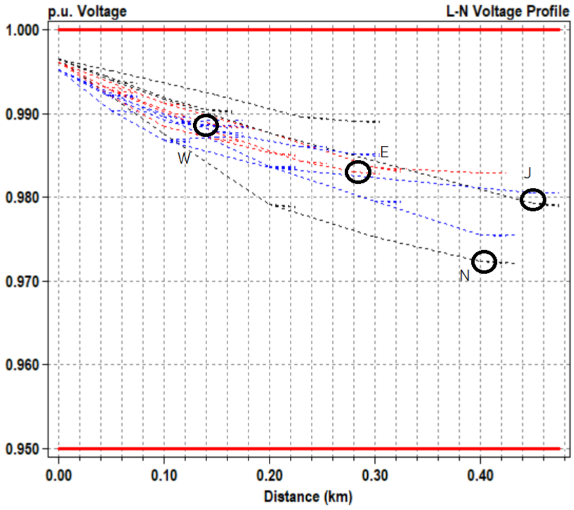

Figure 2-16 Voltage Profiles Distribution after adoption of 600W EPCs within the LV Network

Figure 2-16 shows that LV distribution cables can efficiently support new electric cooking load and voltages can be maintained within acceptable limits, meaning that overall distribution losses while transferring power to 600W EPCs are low. Busbars W, E, J and N have been highlighted (see Figure 2.3) to show the nodes at each of the four feeders where highest voltage drops are expected.

2.6.3. Impact of 1kW EPCs on LV Network

The final scenario presents the impact of connecting 1kW EPCs onto the LV network in each of the households. Figure 2-17 shows that the maximum power required to support all households cooking with 1kW EPCs reaches a midday peak of 85kVA, based on the estimated cooking and non-cooking load profiles as in previous sections. The 50kVA limit on the distribution transformer has been breached for sustained periods. With the same assumptions in place as per the 600W EPC penetration case and the same specified grid infrastructure (see section 2.6.2), it is determined that a maximum of 45% of all users could use these EPCs without any impacts on network performance or operation.

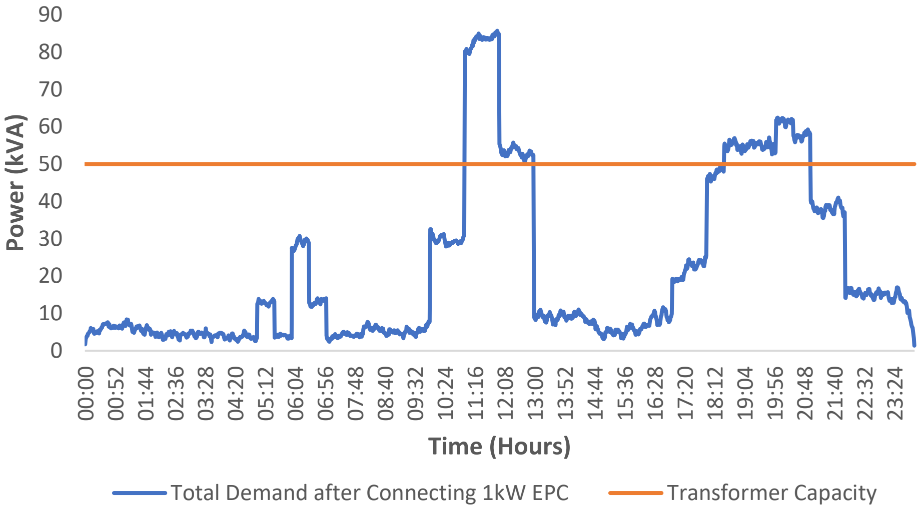

Figure 2-17. Power Consumption after Connecting 1kW EPCs

As for the other scenarios, voltage profiles after the adoption of 1kW EPCs were also investigated. These were generated for the peak midday demand when the network is expected to experience peak loading. The results indicating voltage distribution are presented in the Figure 2-18.

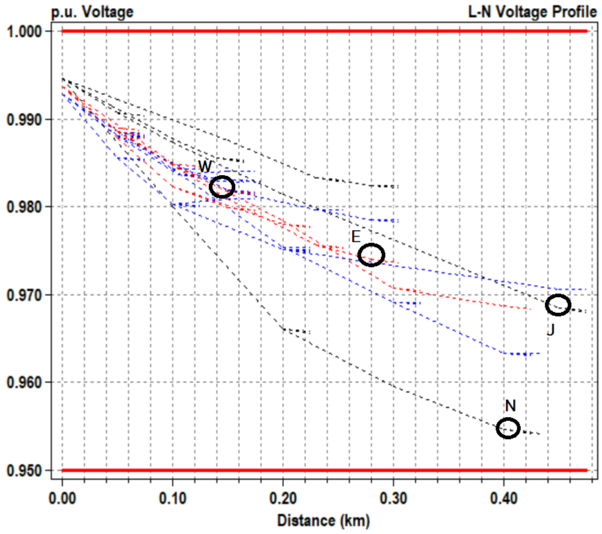

Figure 2-18. Voltage Distribution after adoption of 1kW EPCs

Figure2-18 shows that even with all households adopting EPCs (again assuming that, as previously, the transformer is upgraded according to the increased power requirements; from 50kVA to 100kVA) the maximum voltage drop does not exceed the recommended limit of 5% (modelled voltage drop is 4.5%). As such, although distribution efficiency is affected by all households adopting 1kW EPCs, the modelled system still provides adequate performance and can safely support the load.

Under the investigated conditions for a typical LV network in sub-Saharan Africa, the maximum current limit of the existing cable is significantly higher than requested, while providing power to the electric cooking systems. As a result, it was concluded that the distribution network cables currently installed can serve electric cooking appliances and/or other significant load growth without a need to upgrade.

2.7. Summary of the LV Network Studies

The LV network studies presented in this report provide understanding of a typical LV distribution network configuration in sub-Saharan Africa, downstream from the secondary substation. The studies carried out analyse loading on the substation and voltage profiles at different busbars of the existing infrastructure. A summary of the findings for each scenario considered is presented in the Table 8.

Table 8. Electric Cooking – Summary Table

Scenario	**At 100% eCook penetration** **✓ within constraints** **✗ exceeds limits**		**Comment** **Approx. viable eCook penetration (within voltage and power constraints)**
	Voltage	Power	
300W Rice Cookers	✓	✓	100% adoption can be supported
600W EPC	✓	✗	75% adoption can be supported
1kW EPC	✓	✗	45% adoption can be supported. Voltage drops at network extremities approach limits

In general, voltage levels within the whole LV network with a high penetration of households with electric cooking systems can be maintained. Based on the analysis conducted, the maximum voltage drops should not exceed 5% between secondary substation and end-customer during normal operation. Furthermore, it is not clear to what extent that any local power quality regulations will be enforced and/or measured concerning voltage or other network parameters by the incumbent DNO (distribution network operator). Despite this fact, the LV network can still distribute power within its safe conditions and the thermal limits of 50mm^2 ABC cables should not be exceeded.

The analysis performed for scenarios considering the use of 300W rice cookers and 600W EPCs identifies that high penetration of electric cooking appliances can be achieved without exceeding any limits on the LV network. It is estimated that approximately 75% of households equipped with 600W EPCs can safely cook on electricity and in the case of 300W rice cookers, LV networks can withstand new cooking loads for 100% of users under the modelled specifications.

The only large technical constraint identified within the LV network was associated with the size of the distribution transformer when modelling the highest-powered cooking device considered in this study (1kW EPC, see sub-section 2.6.3). However, under the configuration studied, approximately 45% of households connected to the secondary substation could still be equipped with such cooking appliances without breaching constraints.

As such, the limiting factor in accommodating high levels of eCook penetration on LV networks is likely to be the size of the distribution transformer. To support penetration levels higher than the limits identified by this study, network planners need to consider increasing the size of the distribution transformer which is currently selected, considering not only cooking loads, but also the likely increase in non-cooking baseload demand. For existing (and in some cases for new) network deployments other techniques may be more cost effective, including Active Network Control concepts and/or Demand Side Management solutions (see Section 4 for more details).

Box 1: Dense “pockets” of new electrical demand present challenges to networks while other characteristics present opportunities for rapid eCook adoption

The above proportions of eCook appliances which the analysis indicates can be supported by LV networks assume that adoption is evenly spread across the network. However, scenarios where there is rapid adoption of electric cooking devices (or other high-powered electrical appliances) in dense pockets across the network could also pose challenges. This is especially important if located at the extremities of the distribution network or where the network is weak. For example, groups of households in an affluent neighbourhood on the outskirts of a city may all choose to adopt electric cooking within a short period as a result of one or two early adopters recommending them or seeing a targeted marketing campaign – similar issues are being investigated on European networks regarding the adoption of electric vehicles. DNOs may find it difficult to identify localised issues like this before they happen when looking at overall grid behaviour, and therefore efforts to affect a transition to electric cooking need to be coupled with enhanced monitoring of demand. Starting to cook with electricity, may also lead households to purchase and use other electrical devices in the kitchen (e.g. fridges, kettles, toasters etc) and also outside the kitchen (e.g. TVs, computers etc) which would exacerbate this issue.

On the other hand, by investigating power generation and transmission system characteristics of particular networks, “grid zones” may be identified which have the capability to support growth in adoption of electric cooking (and other high powered electrical devices). Such characteristics will include demonstrating limited voltage fluctuations, a strong transmission system, proximity to generation units and adequate generation capacity and responsivity.

3. Off-grid Microgrid System

The following section of the report considers the adoption of electric cooking systems on existing off-grid microgrid infrastructure. The model analysed is based on the most common source of power generation across the Global South – a solar PV system, with a backup battery and inverter producing AC power supply distributed to end customers.

Out of several different solar microgrid system providers (each introducing different system specifications), the model used to analyse the adoption of electric cooking devices was based on a specification provided by Powergen. They have already deployed EPC systems at the microgrid level within several sites, specifically selected due to having adequate headroom, and have proven that appropriate system operation can be maintained while providing electricity for the additional loading these cooking appliances bring [13]. The layout of the microgrid considered in this analysis is presented in the Figure 3-1. It consists of 88 households supplied from a single generation and storage unit located in the central location on the system.

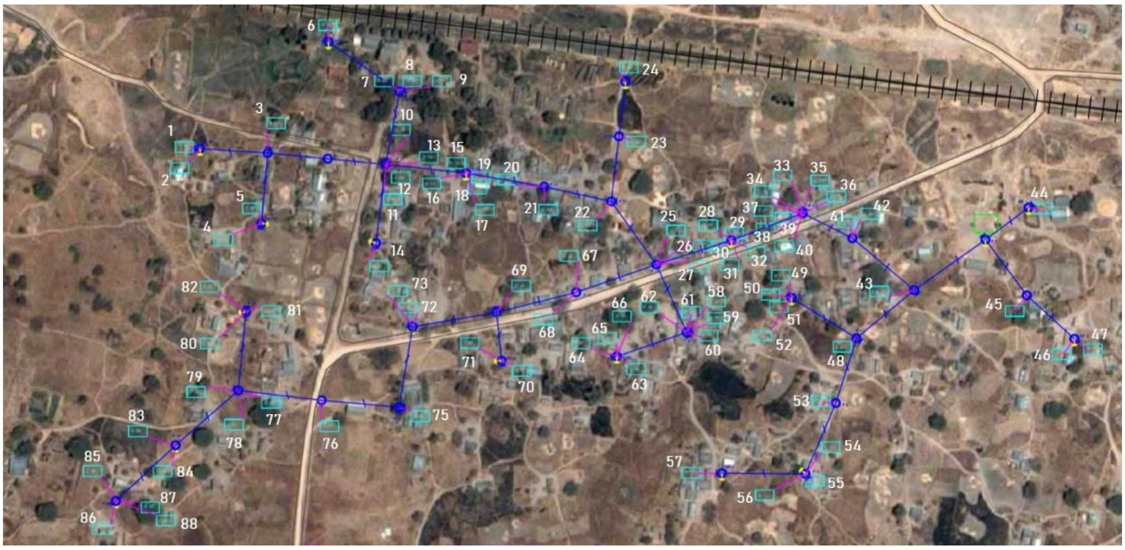

Figure 3-1. The Layout of the Powergen Microgrid System

With the network topology of the microgrid established, the system was modelled in OpenDSS where additional power flow and voltage analyses were performed. Coordinates of the network were estimated based on the topology seen in Figure 3-1Figure 3- and demand profiles were randomly allocated to all 88 households connected within the system.

The local household demand for off-grid systems are typically limited in comparison with users who are connected to the national grid due to a number of factors including higher costs of energy offered by microgrid providers and lower capability to pay for those who live in rural regions, where off-grid systems are typically deployed. As a result, household demand connected to the microgrid is primarily dominated by category 1 and 2 users (see Section 2.1), with the occasional user owning a small refrigerator (category 3). An estimated 24-hour demand profile presenting consumption patterns within the Powergen microgrid is illustrated in the Figure 3-2Figure 3-.

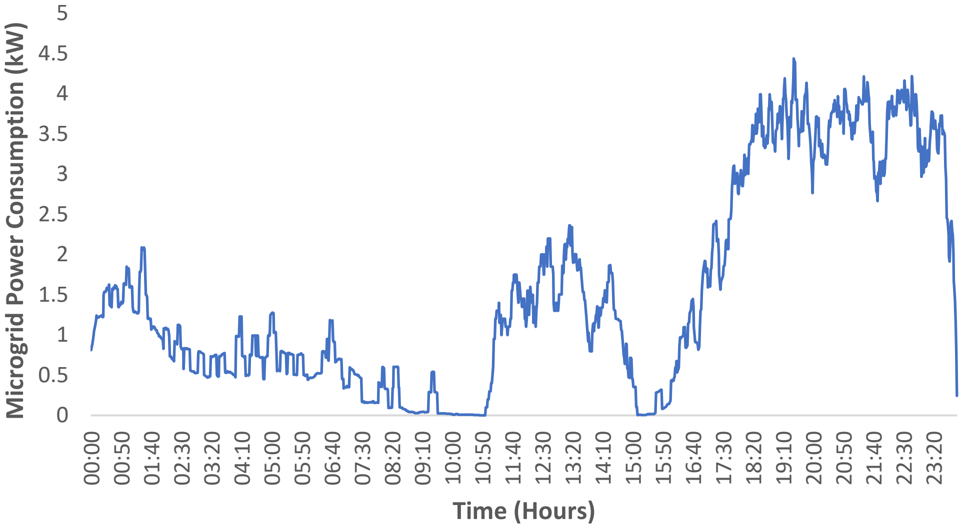

Figure 3-2. Estimated Power Consumption Profiles within the Powergen Microgrid

The microgrid was sized according to Powergen's specification. It is a three-phase AC system with an ABC Cable of 50mm^2 (this is the same specification as most LV distribution networks in sub-Saharan Africa, as explained in Section 2). The service lines are modelled as single-phase 16mm^2 ABC cables. The maximum power consumption allowed by a single household is 2kW - enough to introduce electric cooking devices consuming 1kW. The size of the inverter is matched according to the number of customers connected to the system. The standard module of 3kW peak is installed for approximately 50 customers. Therefore, for a microgrid of 88 households, a 6kW inverter was selected [14].

Based on the given assumptions, it is likely that under this microgrid specification, the principal limitation for widespread adoption of eCook will be the ability to support the end user power requirements. As a result, high adoption levels of electric cooking appliances without system rearrangements could be difficult to achieve. These technical issues can be mitigated by adding additional inverter modules in parallel to the existing ones, to match microgrid capacity with power demand required by eCook systems. Alternatively, a diesel generator with capabilities to provide adequate levels of power capacity to support electric cooking demand could be introduced. Such systems present higher levels of operational efficiency while being heavily loaded which might make electric cooking within off-grid environment a more feasible opportunity [15]. However, assessing the generation capacity of microgrids relative to adoption levels of electric cooking is beyond the scope of this networks study. As such, the following analysis only considers the cable sizes and their ability to support the new loading from electric cooking.

3.1. Voltage Profile Analysis under Pre-eCook Scenario

Voltage drops were expected to be <4% (acceptable limits set by Powergen) in the microgrid under the pre-eCook scenario, particularly considering the very low demand at the household level for people relying on off-grid systems. This has been verified based on the OpenDSS model developed which indicates voltage distribution across the system at the After Diversity Maximum Demand of 100W at each household, as specified by Powergen. Voltage profiles within the microgrid network are illustrated in the Figure 3-3 below.

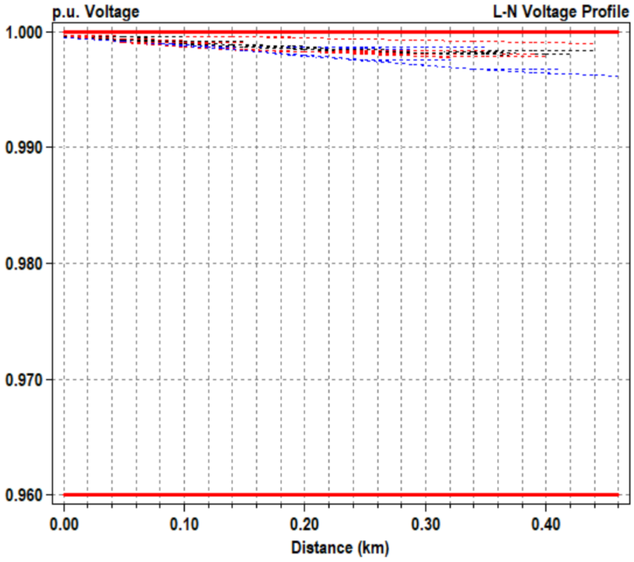

Figure 3-3. Voltage Distribution under Pre-eCook Scenario for a Powergen Microgrid

Figure 3-3 illustrates that under a baseload scenario with no eCook loading, the Powergen microgrid experiences very low voltage drops of less than 0.5% which suggests that cables installed can support significantly higher power transfers than required for the existing baseload demand.

Box 2: National microgrid regulations can enhance ability to support electric cooking adoption

Installation of higher rated cables for the microgrid considered is thought to be due to national regulations for off-grid systems in Tanzania. Regulation influences of this type can guide microgrid designs, making them compatible with the national grid. For example, when/if national grid extension reaches a community, only minimal infrastructure changes are required and microgrid operators are eligible for Independent Power Producer agreements [16]. Planning decisions at the microgrid design stage supported by a well-informed regulatory environment can support growth in adoption levels of electric cooking (and other electrical appliances).

3.2. Voltage Profiles after Connection of Electric Cooking Appliances

The following part of the microgrid study involves investigation of the network behaviour after connecting electric cooking devices. The simulation has been performed to present voltage dynamics in the network after adoption of 1kW EPC at the peak load demand experienced by the system (based on cooking diaries from Murambi village). To analyse voltage profiles of the system after connection of EPCs at each household, limitations due to installed inverter, PV array and energy storage were ignored and 230V slack bus producing constant voltage, capable of providing an infinite source of power was introduced. This assumption was undertaken purely to investigate the performance of the microgrid cables. Figure 3-4 presents voltage profiles across the system. It also indicates voltages at households 1, 57 and 88 (see Figure 3-) which are connected to ultimate sections of each of three feeders in the microgrid where highest voltage drop is expected.

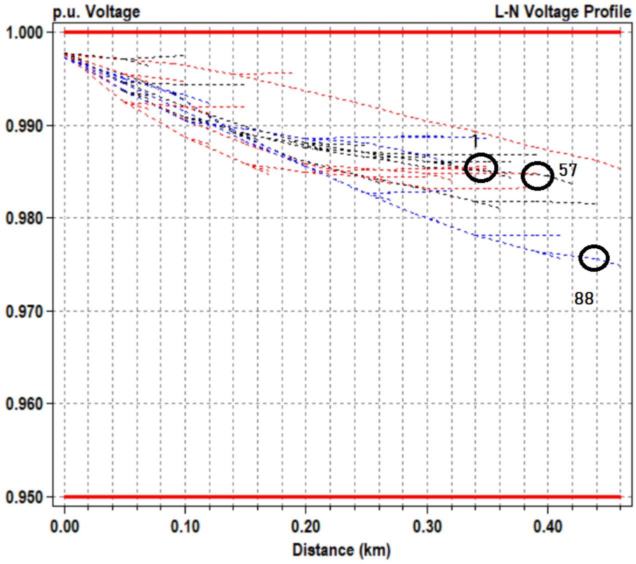

Figure 3-4. Powergen Voltage Profiles after connected 1kW EPC at each household within the Microgrid System.

Based on the analysis of the voltage profiles, the maximum drop experienced by the microgrid can reach approximately 2.5% from the nominal (maximum recommended by Powergen is 4%), therefore, it can be concluded that efficiency of power distribution is high enough to withstand significant cooking loads. In fact, the overall voltage drops within the microgrid system are lower than for the LV network supporting 1kW EPC. This is because of significantly lower baseload power demand presented by off-grid microgrid customers.

3.3. Microgrid Capacity Limitations while Installing eCook Devices

The capacity of the power inverter converting DC voltage to AC for power distribution in the microgrid is the first element requiring upgrades when adopting electric cooking devices. Currently, off-grid household demand is specified to support electrical appliances of lower power requirements than those needed to support cooking devices and so the installation of rice cookers or EPCs would require microgrid upgrades.

Currently, most LED bulbs (the most popular appliances within off-grid environment) deployed on off-grid microgrid consume between 1W and 5W and phone chargers typically require around 2W [17], [18]. As a result, the real ADMD may not exceed 20W per household. Some households increase their energy requirements, through purchasing TVs (~20W) and refrigeration systems (~60W). Given the increase in power consumption as a result of using electric cooking appliances the headroom on existing microgrids may only allow a small number of low powered electric cooking appliances to be supported between a number of households without the need to reinforce the microgrid system.

To reach a higher number of households using electric cooking devices within the microgrid system, an upgraded power inverter module will therefore be required. The capacity issues can be also mitigated by installation of distributed battery systems at a household level charging during off-peak hours to later support electric cooking appliances without overloading the existing inverter.

Other difficulties when matching new demand are associated with legacy lead-acid batteries. This technology has been fundamental in providing power supply for lighting at night in a great many operational micro- and mini-grids in sub-Saharan Africa but issues arise when introducing new demand with high power consumption peaks, such as cooking demand. Introduction of lithium-ion batteries capable of withstanding fast discharge rates can solve these issues. The rapidly falling costs of this technology, longer operational lifecycles as well as greater interest in this technology by solar mini-grid providers means that electric cooking could become a feasible product offered by solar companies in the coming years.

3.4. Other Types of Microgrids as an opportunity for electric cooking adoption

Although existing solar microgrids would require substantial upgrades to provide electricity for cooking devices, other forms of microgrid may already present viability. For example, hydro-based systems often have significantly higher generation capabilities than solar systems. As a result, wide deployment of electric rice cookers has already been noted in Nepal and Bhutan where hydroelectricity is the optimal (and the cheapest) source of electricity for rural, off-grid villages [19], [20]. Wide deployment of electric cooking appliances within hydro systems has been primarily enabled due to the low cost of electricity produced by these types of systems, and more consistent power generation than solar PV.

4. Further recommendations to maximise the feasibility of adoption of electric cooking appliances on LV networks and off-grid microgrids

In Section 2 we analysed three scenarios of electric cooking on LV networks indicating that the network can easily support all customers using cooking devices with low power requirements (such as 300W rice cookers). Under the second scenario where 600W EPCs are used, existing transformers can support up to 75% of households cooking with such devices. Even when households use 1kW EPCs (scenario 3), a 45% penetration level could be supported under the specified network, with increased levels of penetration requiring upgrades to transformers or the use of other solutions.

The off-grid solar microgrid analysis shows that although existing cables infrastructure can support new electric cooking loads, the main limitations are introduced at the inverter stage. As a result, widespread adoption of even low powered electric cooking appliances (e.g. rice cookers consuming 300W) may be difficult to achieve under the existing specifications.

Initial consideration has been given to the ways in which LV and microgrid networks could be improved to accommodate eCook penetration beyond the reported limits. This list is not exhaustive and some of the options considered are summarised in Table 9 below. A thorough review of solutions incorporating a techno-economic comparison would be an informative topic for future study.

Table 8. Different Solutions with potential to improve adoption and accommodation of eCook Devices on LV Network

Conventional Upgrades	
Size-up capacity of a substation (LV Network)	This is the conventional method to increase power capacity to support higher loads. Likely to be expensive (cost of a 50kVA transformer is approximately $12000 for 100 households network [3]).
Installation of Additional Inverter Modules (off-grid Microgrids)	A typical method used to provide higher capacity for new electric loads within the off-grid microgrid system. Sharing load using two or more inverters within the same microgrid system reduces risk of overloading the system with high power appliances including electric cooking. Cost of a single 6kW inverter (similar capacity to inverter sized for Powergen microgrids) can vary between $2500 and $4000 [21].
Use of Active Networks Management and Demand Side Management	
Active Management of Cooking Loads	By using low-cost power converters installed in each household supported by local energy storage it is possible to reduce loading on the LV network or microgrid system (cost of lithium-ion battery ~180$/kWh [22]). Electricity would be used from the energy storage (battery) during cooking cycles as well as by changing setpoints for power consumption of some cooking loads. As a result, overall power consumption of cooking devices could be matched with the maximum loading permitted. Appropriate management of the cooking loads could also prevent higher quantities of cooking devices to switch on at the same time, in order not to overload the network. As a result of this

	Active Management System, higher penetration of cooking loads can be adopted without major, costly network reinforcements.
Demand Side Management (DSM)	To avoid exceeding the maximum transformer capacity, each eCook user may be allocated with a specific time slot for cooking to ensure that maximum transformer capacity is never reached. Introduction of this (relatively) low-cost solution requires deep interaction between eCook users and the network operator providing DSM functions. As a result of introduced DSM, new demand within the LV network/microgrid can be significantly diversified, maximising %-age of households with high power electric demand, including cooking appliances [23].
Introduction of additional capacity within the LV network by installation of Distributed Generation (DG)	Adding Distributed Generation (DGs) units may allow cooking loads the be supported by reducing loading on the transformer circuit. This could result in obtaining higher penetration of households using electric cooking devices without the need to install additional transformer circuits to accommodate new capacity.
Introduction of a Smart Transformer with Additional Back-up Energy Storage supplying LV Networks	This solution, applicable within newly installed LV networks, introduces a transformer circuit fully controlling voltages on the LV network side of the distribution transformer with power electronics. It gives capability to install internal battery storage to support peak loads connected to the LV network as well as during critical events when power system experiences shortages.
Flexible Pricing for Electricity	To avoid overloading the network, cooking load could potentially be controlled by adapting flexible tariffs for electricity use. To encourage behaviour change, such tariff changes could, for example, be indicated by several LEDs installed within the cooker interface. As a result of such arrangement, users would be incentivised to consume cheaper electricity during off-peak periods.

5. Conclusion

This report presents models of two networks which could potentially provide power for electric cooking appliances in sub-Saharan Africa. For LV networks, adoption of 300W rice cookers without exceeding technical constraints can easily be supported. Installation of 600W EPCs can also be supported for a high proportion of users connected under the same secondary substation (approximately 75% of households). For 1kW EPCs, the specified LV network can support up to 45% of households adopting the device. It has also been shown that for 50mm^2 ABC cables which are commonly used on such networks, the maximum voltage drop is within the recommended limits even for 100% adoption of 1kW EPCs and thermal constraints of the cables will not be exceeded. To support electric cooking adoption levels above the identified threshold, LV networks need to address a capacity limitation at the transformers; several options to mitigate this have been offered. The studies were performed assuming optimal functionality of the power transmission system and sufficient generation capacity within such power networks, resulting in supplying adequate voltages to the LV distribution system.

Considering different ‘hub-and-spoke’ solar off-grid microgrids currently requires individual analysis for each system provider due to the diversity of specification being used across sub-Saharan Africa. For the microgrid studies presented in this report, a model was used based on a Powergen network that is representative of an off-grid solar system installed in Tanzania. It has been shown that microgrids with this specification are capable of supporting EPCs after performing some technical upgrades at the power inverter stage. They also require the introduction of additional generation and storage capacity to support high penetrations of cooking loads. It was also verified that adoption of electric cooking appliances does not produce higher voltage drops than specified at the system design stage. As a result, existing microgrids can be purposed to support additional loads brought about through electric cooking in the future.

References

[1] "Energy Sector Management Assistance Programme (ESMAP) - Access to Electricity." [Online]. Available: https://www.esmap.org/node/71201. [Accessed: 29-Aug-2020].

[2] *Guidelines for Human Settlement Planning and Design.*, vol. 1. CSIR Building Construction and Technology, 2007.

[3] H. Louie, *Off-Grid Electrical Systems in Developing Countries*. 2018.

[4] "Tanesco Distribution Engineering Instruction Manual," no. 9th Edition.

[5] Minifra, "Preparatory Survey on the Project for Upgrading, Rehabilitation and Expansion of Substations and Distribution Network in the Republic of Rwanda," 2011.

[6] G. Barnes, S. Jones, and S. Jones, "Guidace for Self-Determination of point of COnnection and Self-Design Approval for Independent Connection Providers," no. 3, pp. 1–52, 2016.

[7] S. Mandelli, C. Brivio, E. Colombo, and M. Merlo, "Effect of load profile uncertainty on the optimum sizing of off-grid PV systems for rural electrification," *Sustain. Energy Technol. Assessments*, vol. 18, pp. 34–47, 2016, doi: 10.1016/j.seta.2016.09.010.

[8] C. Dominguez, K. Orehounig, and J. Carmeliet, "One step further for electrifying rural households in Africa: A novel electricity demand modelling approach," *4th Build. Simul. Optim. Conf.*, no. September, pp. 11–12, 2018.

[9] S. Sewchurran, "Survey and assessment of the impact of embedded generation on the eThekwini electricity distribution grid," no. December, pp. 1–350, 2016.

[10] "5%voltagedrop." [Online]. Available: www.electrical-installation.org/. [Accessed: 20-Aug-2020].

[11] "Voltage Drops." [Online]. Available: https://bralpowerassociate.blogspot.com/2013/10/voltage-drop-calculation-in-cable.html. [Accessed: 12-Aug-2020].

[12] T. Reber, S. Booth, D. Cutler, X. Li, and J. Salasovich, "Tariff Considerations for Micro-Grids in Sub-Saharan Africa," *US Aid*, no. February, p. 30, 2018.

[13] "PowergenEPC." [Online]. Available: https://microgridnews.com/electric-pressure-cookers-minigrids-solving-global-problem-of-biomass-cooking/. [Accessed: 31-Aug-2020].

[14] N. J. Williams, P. Jaramillo, B. Cornell, I. Lyons-Galante, and E. Wynn, "Load characteristics of East African microgrids," *Proc. - 2017 IEEE PES-IAS PowerAfrica Conf. Harnessing Energy, Inf. Commun. Technol. Afford. Electrif. Africa, PowerAfrica 2017*, pp. 236–241, 2017, doi: 10.1109/PowerAfrica.2017.7991230.

[15] A. Stiel and M. Skyllas-Kazacos, "Feasibility Study of Energy Storage Systems in Wind/Diesel Applications Using the HOMER Model," *Appl. Sci.*, vol. 2, no. 4, pp. 726–737, 2012, doi: 10.3390/app2040726.

[16] IRENA, *Policies and regulations for renewable mini-grids*. 2018.

[17] "BBOXX-appliancesSpecification." [Online]. Available: https://www.bboxx.com/products/bpower20/. [Accessed: 31-Aug-2020].

[18] BBOXX Ltd., “BBOXX Home,” London, UK, 2019.

[19] D. Schnitzer, S. Deepa, J. P. Carvalo, D. Ranjit, A. Jay, and K. Daniel, “Microgrids for Rural Electrification : A critical review of best practices based on seven case studies Microgrids for Rural Electrification : A critical review of best practices,” *United Nations Found.*, no. July 2016, p. 122, 2014, doi: 10.13140/RG.2.1.1399.9600.

[20] “MECS-TRIID Project Report (public version) Assessing electric cooking potential in micro hydropower microgrids in Nepal People , Energy and Environment Development Association (PEEDA),” no. March, 2020.

[21] “6kW Solar Power Prices Exposed (With An Important Warning).” [Online]. Available: 20/08/2020.

[22] “Global Market Intelligence,” 2020. [Online]. Available: https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/as-battery-costs-plummet-lithium-ion-innovation-hits-limits-experts-say-58613238. [Accessed: 13-Oct-2020].

[23] E. Impact, “Demand Side Management for Mini-grids Executive summary,” no. April, pp. 1–70, 2019.

APPENDIX A

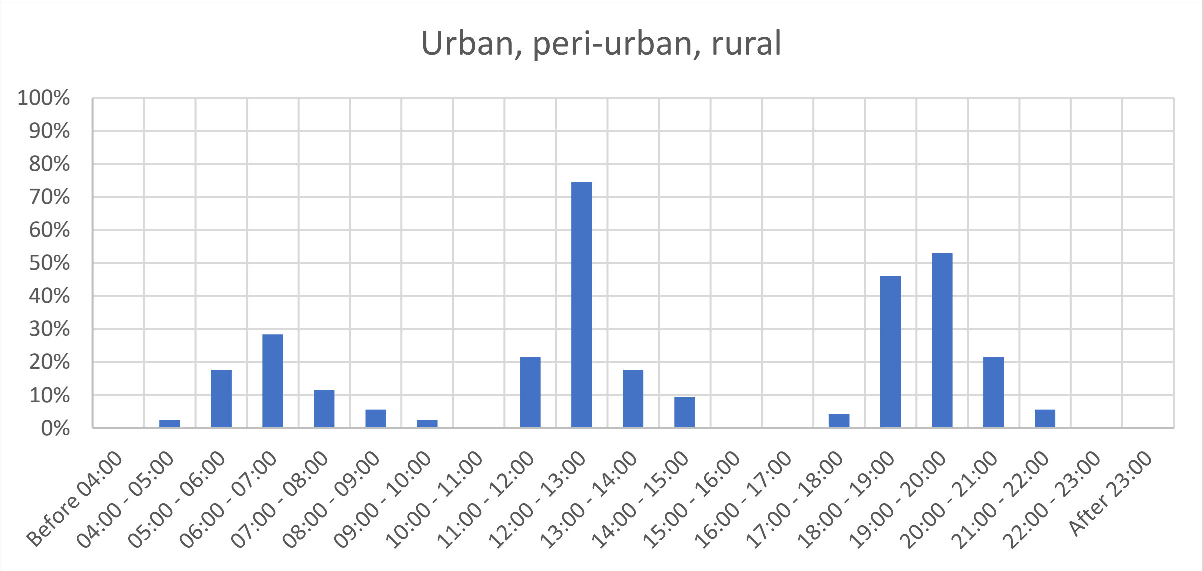

Figure A1. Cooking Patterns in a Malawi (averaged across 3 sample areas)