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Assessing the Techno-economic Feasibility of eCook Deployment on a Hybrid Solar-Diesel Mini-grid in Rural Malawi

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***Abstract*—1.8 billion people have access to electricity although still cook with biomass, causing negative health and adverse environmental impacts. Recent research promoting the use of electric cooking devices (eCook\eCookers) to reduce biomass usage includes data capture, market assessments and eCook device prototyping to give a clearer vision on how people cook and associated costs. However, when dealing with analyses of electrification in rural and remote areas, a lack of information remains for the optimum size and costs of off-grid systems to accommodate eCook loads. The techno-economic modelling software HOMER-Pro is used in this paper to simulate four different mini-grid models to evaluate optimal configurations for the Dedza mini-grid, in Malawi with increased household (HH) eCook use, targeting economic and environmental objectives. The simulation results reveal that model 4 which represents the optimized photovoltaic (PV)/battery/diesel hybrid mini-grid model, provides the lowest Cost of Electricity (COE), less greenhouse emissions, a higher Renewable Fraction (RF) when accommodating eCookers, and as the eCook penetrations increase the COE reduces due to the relative increase in the total annual electric load served (E_{served}).**

***Index Terms*— Demand modelling, electric cooking devices, mini-grids, on/off-grid systems.**

I. INTRODUCTION

Access to modern energy and clean cooking is being addressed widely in developing countries. Globally, three billion people still use biomass to accommodate their cooking needs [1]. By continuing to use traditional cooking methods such as a three-stone stove, high levels of household (HH) air pollution is created, which has severe negative health effects, particularly on women and children. According to the World Health Organization, it is estimated that three to four million premature deaths occur annually worldwide [2]. Greenhouse gas emissions from non-renewable biomass fuels alone reaches a gigaton of CO_2 per year [3] and as much as 25% of black carbon comes from HH cooking, lighting and heating contributing to carbon dioxide warming worldwide [4].

To date, considerable work has been undertaken to increase efficiency and accelerate the implementation of improved cookstoves [5] [4] [6]. New designs are now being produced, using a range of materials and techniques to improve performance and provide the consumer with a choice in cookstove style and size. Significant efforts have also been made towards the use of renewable and low carbon fuels such as liquid petroleum gas, liquid fuel, biogas fuel and solar, reducing the dependency on solid and kerosene fuels [6] [7].

Cooking with electrical devices known as ‘eCook/eCookers’ are becoming an attractive solution to accommodate both health and environmental benefits. The UK research and implementation program “Modern Energy Cooking Services” (MECS) [8] explores this solution, as one of the alternatives to meet the Sustainable Development Goal 7 (SDG 7) ensuring access to affordable, reliable and modern energy for all [9].

Energy poverty also remains a huge challenge facing developing countries in Africa and Asia. According to statistics reported in The Energy Progress Report [10], in 2017 there were still around 840 million people without access to electricity, although this is anticipated to decrease to 650 million people by 2030. This translates into 8% of the global population with 9 out of 10 living in Sub-Saharan Africa. Also, a considerable amount of work and planning is being carried out in Sub-Saharan counties to provide electricity, aiming to improve lifestyles either by on-grid and/or off-grid systems. In most scenarios, costs associated with extending the grid are higher compared to off-grid solutions [11] [12], as targeted communities live in rural areas where load density is low and the cost of components to extend the grid are high.

Many central grid distribution networks in Africa have lines, transformers, fuses and circuit breakers which are heavily overloaded and operate outside their designed limits [13], which influences the quality and reliability of the power supplied. In most distribution networks, power is transmitted through radial circuits to consumers, which presents the challenge of consumer power loss in the case of feeder failure. Losses are another issue when increasing line distance. With the lack of generation mix, wear and tear on existing plants and power infrastructure, along with the absence of operating reserves, the grid can become unreliable and unstable. For example, initial studies conducted on Malawi’s national grid revealed that demand for electricity exceeds the generation available. Consequently, rolling blackouts are scheduled routinely, due to the shortage of power [14] [15]. This is also common in many other developing countries. For the reasons mentioned, off-grid systems, particularly, mini-grids, are viewed as promising solutions to accommodate HH`s electricity needs in rural areas [16] [17].

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Finding the optimal sizes for mini-grid components is an important factor in design, to avoid under/oversizing the system, which may lead to undesirable technical or economic impacts. Therefore, given the momentum towards eCook use in developing countries, combined with global impetus towards rural electrification via mini-grids, it is necessary to consider how ‘fit for purpose’ existing mini-grids are to accommodate increasing eCook demand, or indeed what design considerations or interventions will be required to make them so. A key area for investigation is determining the sizes of mini-grids required to accommodate this new eCook demand, and the level and cost of reinforcement required for existing mini-grids versus other, ‘smarter’ active network management approaches that may minimize the need for reinforcement and allow cost-effective and affordable eCook deployment for developers and consumers.

The objective of this paper is to use HOMER modelling of a Malawian mini-grid to assess and identify the optimal sizing of eCook mini-grids for feasible eCook deployment in terms of size and cost for different eCook penetrations, specifically referring to the number of HHs using eCookers. This paper is organized as follows; Section II describes the mini-grid HOMER model used in this research study. Section III lays out the eCook mini-grid system arrangements and eCook deployment scenarios to investigate the size and cost of eCook mini-grids. The results are set out and analyzed in Section IV. Finally, the conclusion is presented in Section V.

II. MALAWI MINI-GRID SYSTEM

This study uses an existing mini-grid model designed in HOMER, for more information refer to [18]. The original model was designed with a 10% energy shortage and for the purpose of this study the mini-grid size was upgraded to meet 0% energy shortage, to assess and identify the optimal configuration for eCook mini-grids in terms of size and cost.

The geographical location of the system is Dedza in the central region of Malawi [18]. The generation of electricity is solely from renewables based on a 14.1 kW_p photovoltaic (PV) panel, 41.1 kWh battery, 5 kW PV-inverter and 11.6 kW converter after upgrading the system. It supplies power through an AC connection to a village of 50 HH and 10 businesses (local shops and barbers). A simplified diagram of the mini-grid model is shown in Fig. 1.

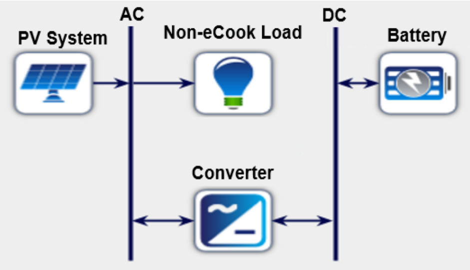

Fig. 1. Malawi Mini-grid Schematic

To choose the optimal eCook mini-grid, from the mini-grid models developed in HOMER and with the objective of maintaining the system’s reliability and efficiency, the models are analyzed considering the following simulation results:

- Energy Shortage (the maximum allowable energy shortage is 0%)
- Renewable Fraction (RF)
- Net Present Cost (NPC)
- Cost of Electricity (COE)
- CO_2 Emissions

A. *Model Input*

The input data used for the Malawi mini-grid are shown in TABLE I and the project’s lifetime is taken as 20 years. To calculate the PV output power, HOMER uses the mini-grid location to import the solar resources data from NASA surface metrology and Solar Energy. The model uses an annual average solar radiation of 5.33 ($KWh/m^2/day$) with low and high sensitivities of 5.02 $kWh/m^2/day$ and 6.42 $kWh/m^2/day$ respectively. The battery is set to operate at an initial and a minimum state of charge (SOC) of 100% and 20% respectively. To evaluate the NPC and the COE, the expected inflation rate and the nominal discount rate are taken to be 6% and 10% respectively.

TABLE I. Malawi Mini-grid Characteristics

Component Size	**Value**	**Initial Capital Cost**	**Replacement Cost**	**Lifetime**
PV array size	4.8 kW_p	1,950 $	1,950 $	25 years
Diesel Generator	0 kW	500 $	500 $	15,000 hours
Lithium-ion Battery	27.6 kWh	15,318 $	15,318 $	10 years
Converter	8 kW	3,574 $	3,574 $	10 years

B. *Demand Load Profile*

1) *Non-eCook Load*

This refers to the domestic and commercial loads which represent ‘typical’ electricity consumption of a small rural village. It represents the total power used for lighting, phone charging, radio, TV and refrigerators [18]. The hourly electricity consumption for a typical day is illustrated in Fig. 2, showing that demand is expected to peak in the evening at around 8 pm and 9 pm, while morning demand (between 0 am and 9 am) is very low and increases as it reaches midday.

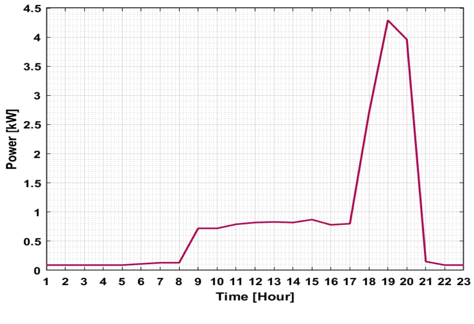

Fig. 2. Non-eCook Load Profile for 60 Customers (50 HHs and 10 businesses)

2) *eCook Load*

As the eCook project [8] is in its early stages, eCook power consumption data are lacking. This study used the load profile established from the ‘eCook Kenya cooking diaries’ report [19] as the staple food and cooking methods have common factors. In each HH the average hourly eCook power consumption varies considerably. Aggregating all the daily load profiles together without the non-eCook load (see Fig. 3), gives a smother consumption with three distinct peaks; morning, midday and evening, with the evening peak being the most intense.

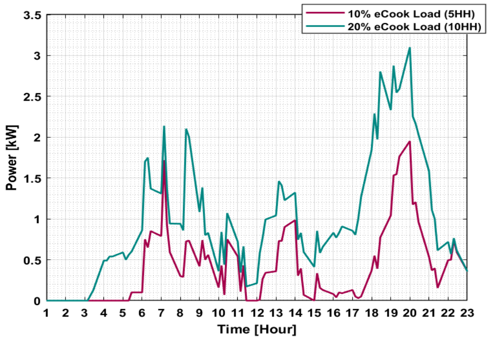

Fig. 3. eCook Daily Load Profile for 5HHs (10%) and 10HHs (20%)

III. ECOOK MINI-GRID SYSTEM ARRANGEMENT AND ECOOK DEPLOYMENT SCENARIOS

C. *eCook Mini-grid System Arrangements*

Four different mini-grid system models were developed in HOMER to evaluate the optimum size and cost of eCook mini-grids.

1) Determine eCook penetrations on fixed mini-grid (PV/Storage mini-grid): The upgraded Malawi mini-grid with 14.1 kW_p PV array, 41.1 kWh lithium-ion battery, 5 kW inverter and 11.6 kW bidirectional converter was tested with different eCook penetrations. This model investigates the ability of the system to accommodate eCookers without any further reinforcement.

2) Determine mini-grid size/configuration for varying eCook penetrations (PV/Storage and optimized Diesel Generator mini-grid): In this model an optimized diesel generator is added to the Malawi mini-grid (model 1). In HOMER, this type of generator automatically sizes itself to serve the load demand not met by the PV and the battery with the objective of ensuring 0% energy shortage.

3) Determine mini-grid size/configuration for varying eCook penetrations (optimized PV/Storage mini-grid): The mini-grid is designed to provide 100% renewables. It comprises of a PV and battery without a diesel generator. HOMER was used to size the PV array, the battery, inverter and the bidirectional converter required to supply various eCook penetrations.

4) Determine mini-grid size/configuration for varying eCook penetrations (optimized PV/Storage/Diesel Generator mini-grid): This model is based on a hybrid mini-grid with a PV array, battery bank and a diesel generator as well as a bidirectional converter and an inverter. The sizes of each of these components are calculated using the HOMER optimizer.

D. *eCook Deployment Scenarios*

In this paper eCookers are used by domestic HH only. Each of the system’s models stated earlier are simulated to calculate and analyze the size and cost of eCook mini-grids for these systems, where the number of HHs using eCook devices is increased. All system models are simulated with varying levels of eCook penetration, ranging from non-eCook load to 10%, 20%, 50%, 80% and 100% eCook penetrations, (where 100% refers to all 50 HH using eCooker).

IV. RESULTS AND ANALYSIS

E. *Homer Mini-grid Models*

The summary of the eCook mini-grid sizes for different eCook penetrations are shown in TABLE II. When connecting different levels of eCook to the Dedza mini-grid without any reinforcement, the additional load imposes a constraint on the grid, translated into an increase in the energy shortage due to the limitation of the PV power and battery. This system has the capability to accommodate 10% eCook with an energy shortage of 3%. As the number of eCook devices increases, demand cannot be met resulting in an increase in energy shortage; for a 100% eCook, the energy shortage is 67.2% (refer to Fig. 4).

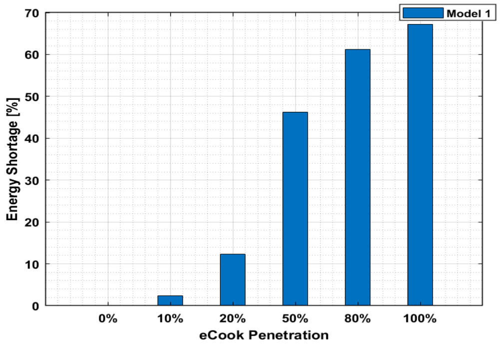

Fig. 4. Energy Shortage for Model 1 for Different eCook Deployment Scenarios

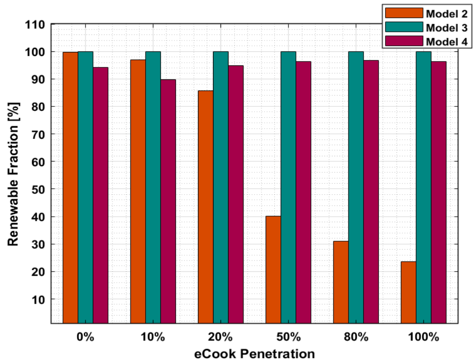

Fig. 5. Renewable Fraction for eCook Mini-grid Models

When adding a diesel generator, 100% of total demand (non-eCook load plus 100% eCook load) is satisfied, as the diesel generator becomes active when the PV is not producing enough energy, usually during early mornings and evenings. As more eCookers are added to the system, an increased amount of fuel is burnt, resulting in a reduction of renewable energy contribution, (Fig. 5 and Fig. 6) along with an increase in CO_2 emissions and other pollutants. To accommodate 100% eCook the RF is 23.5% (Fig. 5).

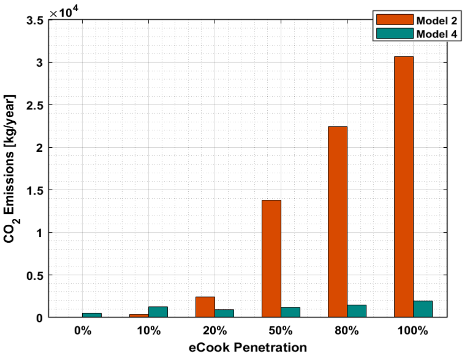

Fig. 6. CO_2 Emission for eCook Mini-grid Models

TABLE II. Component Sizes for eCook Mini-grid Deployment Scenarios

Models/ Scenarios		PV array size	Diesel Gen	Battery	PV-inverter	Converter
		kW$_p$	kW	kWh	kW	kW
1	0%	14.1	0	41.4	5	11.6
	10%					
	20%					
	50%					
	80%					
	100%					
2	0%	14.1	13	41.4	5	11.6
	10%		14			
	20%		16			
	50%		20			
	80%		25			
	100%		28			
3	0%	14.1	0	41.4	5	11.6
	10%	18.4		55.2	5	12.3
	20%	28		69	5	14.3
	50%	92.7		82.8	15	22.1
	80%	119		124	15	33.2
	100%	190		124	20	24
4	0%	10.5	13	27.6	5	7.69
	10%	15.1	14	27.6	5	8.23
	20%	24.5	16	41.4	10	10.3
	50%	47.9	20	69	10	13.9
	80%	65.5	25	96.6	15	19
	100%	81.1	28	110.4	20	21.6

The proposed solutions of the system model 3 arrangement guarantee 100% RF with 0% energy shortage; however, this results in the need for larger mini-grids in order to generate adequate power to supply high penetration for eCook devices. It should be noted that in this model, there remains a large excess of energy generated from the PV. This corresponds to a situation where the battery is already fully charged, and the production exceeds consumption. An exploitation of this excess implies the need for larger batteries which are less economically viable. In this model the mini-grid components are oversized to meet the peak demand. Setting up a hybrid system for model 4, the PV, the battery and the converter are scaled down compared to the values of model 3, since, the diesel generator is added to the model to provide the required capacity when there is a lack of energy from the PV and the battery is fully discharged. This occurs especially at peak times of the day and during periods of heavy rain. In such models, the excess of electricity and the CO_2 emissions are reduced and there is a better exploitation of the solar resources as the RF is within 90% for the various eCook penetrations. The solutions evaluated from the hybrid mini-grids model guarantee in general the best setup for meeting the minimum environmental and economic values compared to model 2 and 3.

F. Economic Evaluation

Fig. 7 and Fig. 8 prove that the system model arrangement 4 which proposes hybrid eCook mini-grid with optimized PV /battery/diesel generator is the most economical of all models in this study, as it guarantees 0% energy shortage, low emissions and high RF. Focusing our analysis on model 4, from TABLE III the COE is the highest at 10%. When increasing the eCook load, the COE continues to decrease (see Fig. 8) due to the increase in the annual total electric load served (E_{served}).

TABLE III. NPC and COE for Model 4 for Different eCook Penetration

eCook Scenarios	0%	10%	20%	50%	80%	100%
NPC ($)	143,864	152,595	170,157	210,418	252,374	279,265
COE ($/kWh)	1.47	1.05	0.813	0.56	0.466	0.428

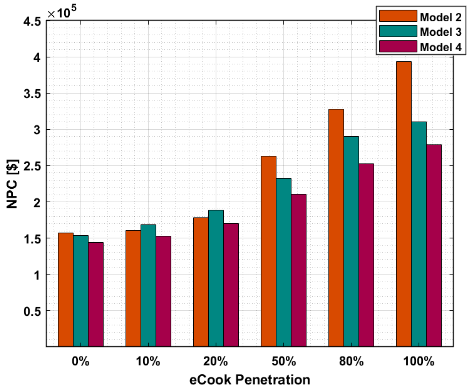

Fig. 7. NPC for eCook Mini-grid Models

Equation (1) shows that the COE as directly proportional to the total annualized cost ($C_{ann,tot}$) and inversely proportional to the E_{served}. Therefore, as the eCook penetration increases from 10% to 100% resulting in a greater increase in E_{served} (351%) compared to the increase in $C_{ann,tot}$ (83%), there is also a notable reduction in COE. Table III shows a 60% reduction in the COE for 100% eCook deployment compared with 10% eCook deployment.

$$COE = \frac{C_{ann,tot}}{E_{served}}, \quad (1)$$

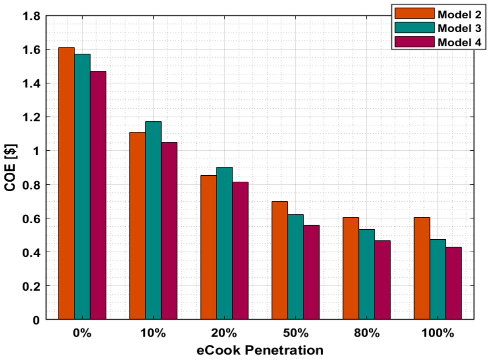

Fig. 8. COE for eCook Mini-grid Models

V. CONCLUSION

Connecting additional loads such as eCook devices present high risks to the power grid in developing countries, where the grids are weak. eCook research to date has concentrated on collecting data for cooking diaries and market assessments, however no studies have assessed key power network parameters such as voltage stability, power losses, power quality and reliability. Off-grid systems, particularly mini-grids could help in the uptake of wide-scale eCook devices and it is therefore important to understand the operational nature of these devices and their impact on power systems performances to enable connecting them to mini-grids in the future. This paper has studied the technical, environmental and economic aspects of eCook mini-grids in a Malawian context which could be applied to rural areas in other less developed countries. Various adaptable mini-grid models and eCook deployment scenarios were simulated in HOMER-Pro.

This research has relevance for governments, practitioners and researchers as it gives an insight into the design considerations of eCook mini-grids in terms of size and cost, required to accommodate different eCook penetrations. Also, it proves that supply becomes cheaper as demand becomes higher, for as the eCook penetration increases, the COE decreases, due to the relative increase in E_{served}. To further decrease the cost of electricity the load factor could be improved by shifting the evening peak electrical load to non-peak times and where there is excess of PV generation.

To the authors knowledge, there is a limitation for measuring the energy consumption of meals when cooking with electricity in developing countries, particularly in Malawi, together with the lack of understanding of the technical impacts of eCookers on mini-grids. The next step in this research will be to collect eCook power consumption data and create load profiles (with/without eCook), as well as using the hybrid mini-grid sizes presented in this paper to model eCook mini-grids to test the system with/without eCook loads and investigate the effect of eCook penetrations on the key power network parameters.

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