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Bridging the Affordability between Battery-Supported Electric Cooking and Conventional Cooking Fuel

Shafiqa Keddar *, Scott Strachan * and Stuart Galloway

Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow G1 1XQ, UK
* Correspondence: shafiqa.keddar@strath.ac.uk (S.K.); scott.strachan@strath.ac.uk (S.S.)

Abstract: Cooking with electricity (eCook) in low-and-middle-income developing countries is still an expensive option compared to using conventional fuels such as charcoal and firewood, so there is a need to identify solutions to make it affordable for all in line with the targets of SDG7. The initial aim of this paper is to understand and provide a comparative analysis of the cooking energy costs through a range of contextualized cooking scenarios—when cooking either with conventional fuels (e.g., charcoal, firewood) or with eCook appliances (e.g., electric pressure cookers (EPC) or hotplates), that are connected to and supplied from an integrated or portable battery (eCook battery). The cooking cost for the eCook cooking scenarios is assessed with and without fuel stacking where a degree of eCook exists alongside other conventional fuels. These studies offer a more realistic concept of the cooking practice to characterize the best fit for cooking scenarios and the main factors required to close the gap between the energy cost of conventional fuel and eCook batteries. The results suggest that to close the affordability gap between firewood and battery-based eCook, three main factors must be considered when estimating the cooking cost: the non-market cost of firewood; ensuring a low mini-grid tariff that is within range of the national grid tariff; and using an optimal eCook battery size with the capability to meet the required demand. In fact, when taking these factors into account; for the 2022 analysis, cooking 100% using an eCook battery is in a range of USD 29–30/month implying that there could be an opportunity for parity when the firewood cost reaches USD 29/month. The same applies to the cooking prediction costs for 2030, reducing further to USD 20–21/month. However, if the firewood is harvested sustainably, ensuring it is high in quality and dry, it would be difficult for battery eCook to compete. It should be emphasized that this research has relevance for governments, practitioners, and researchers.

Keywords: battery-supported eCook; clean cooking; cooking energy cost; fuel stacking; low-and-middle-income countries; mini-grids

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1. Introduction

The use of traditional cooking stoves in rural Sub-Saharan Africa has serious environmental, social, economic and health implications including harmful emissions of black carbon, an estimated four million premature deaths annually [1], local forest degradation due to unsustainable fuel collection [2] and the loss of time spent while gathering fuel that could range from 1.5 to 5 h as the distance travelled for collecting wood could involve several kilometres in rural areas [3]. Consequently, alternative solutions such as electric cooking (eCook, as referred to throughout this paper), including electric pressure cookers (EPC), induction cookers, hotplates or rice cookers have the potential of bringing considerable health, development, and environmental benefits [4]. ECook devices can be directly connected to the power supply or connected to and supplied by an integrated or portable battery (eCook battery). The United Nations Sustainable Development Goal 7—"access to affordable, reliable, sustainable and modern energy by 2030", has inspired the research presented in this paper, which was conducted in partnership with the UK's Modern Energy Cooking Services (MECS) program [5], which has conducted considerable research and field trials to accelerate the transition from biomass to electricity for cooking, and which has demonstrated the considerable promise of eCook [6–9].

Central grid distribution networks in many developing countries face a series of challenges [10], where parts of the systems are overloaded due to the inconsistency between demand and generation. Consequently, transformers, fuses and circuit breakers operate beyond their design limits causing frequent failure and unscheduled outages as well as scheduled load shedding. In most distribution networks the power is transmitted through radial circuits to the consumers, meaning supply restoration through network reconfiguration is not viable in the case of a failure of any feeder; no power will be transmitted to the associated consumers. High power losses and phase imbalance are other factors that reduce the strength of the grid and cause regular blackouts. With the lack of generation mix, wear and tear of existing plants and power infrastructure, as well as the absence of operating reserves, the grid becomes unreliable and unstable. In addition to this, the perception of high energy prices when cooking with electricity act as a barrier to moving towards eCook.

Therefore, it is evident that connecting wide-scale eCook loads to the national grid is highly challenging. As a result, Sub-Sahara Africa needs to build more reliable power systems, with a prime focus on transmission and distribution. This should also centre on scheduled maintenance, reducing power outages [11]. Currently, this sector is ranked as one of the worst in the world and enormous sums of capital investment are required if the continent is to achieve reliable electricity supply for all. This is estimated to be almost a fourfold increase in current investment levels, equating to $120 billion a year until the year 2040 [10,11]. However, gaining the financial backing needed for energy projects only be achievable if the efficiency of utilities is improved and guaranteed, along with security and stability in the financial sectors in the countries concerned.

To accelerate electricity access in conjunction with eCook, off-grid solutions particularly mini-grids are essential, as they offer advantages over connections to the main grid, such as enhancing the reliability of supply, improving quality of power, better environmental performance and accommodating consumer electricity needs in remote areas, where most of the population is located. Over the past decade, the number of solar/solar-hybrid mini-grids installed globally has increased from 60 to 2099 [12] and so this is not simply a niche area. Mini grids can therefore open up the energy sector to independent power providers and expedite electricity access in rural regions with limited prospects of seeing the main grid extend to their location any time before the SDG target date of 2030.

In terms of the mini-grid network studied in [13], an innovative smart eCook battery management system (EBMS) was developed to alleviate the impact of 'conventional' direct connected eCook, by using integrated eCook batteries, which can be charged by the mini-grid to distribute demand, as well as to increase the quality of the charging process. the EBMS actively communicates the state of the grid and then decides on the eCook battery charging rate (C-rate) set-point required to address the network constraints. In addition to this, recent studies by the Energy Sector Management Assistance Program (ESMAP) [14] and MECS [15] examined the cost of cooking with electricity (from the national grid or mini-grid) and the costs of traditional fuels that are required for stacking or as the baseline. The results show that there is a potential for eCook in urban areas for grid-connected households (HHs) due to the low tariff, as well as for peri-urban mini-grid HHs when the tariff cost is expected to fall to $0.25–$0.38/kWh by 2025. With further continuation of the research work seen in [13] which focused on the technical viability of eCook battery on a hybrid photovoltaic (PV)/diesel mini-grid, the research carried out in this paper assesses the economic affordability of it in developing countries.

Due to the lack of research, there is an absence of literature on HH level eCook battery cooking costs in a PV/diesel mini-grid. Therefore, it is necessary to study and understand the upcoming cost trends when cooking with eCook batteries. When considering the challenges of rapid and wholesale eCook adoption of 100% in rural areas, where affordability remains a significant barrier, eCooking penetration may be more gradual, and intermediate, transitional solutions may be required. HHs in rural areas are likely to have lower spending power for cooking fuels and therefore less ability to pay for modern energy cooking services [16]. Additionally, there may be a reluctance to change cooking methods, as these practices have cultural relevance in many communities, and the food may not taste the same, as well as potential resistance to cooking in batches to reduce overall energy consumption. Evidence also shows that eCook is abandoned by some communities in the winter months, reverting to traditional wood stoves, as this also provides heating for the homes while cooking [17]. Therefore, the solution could be to move towards fuel stacking, helping phase the transition rather than moving directly towards 100% cooking with electricity.

With such an approach, and in time, users may become aware of the benefits of the cleaner options, which may influence their decision-making. In this context, this research aims to explore the economic viability of eCook compared with the use of predominant traditional fuels (charcoal and firewood) and, liquid petroleum gas (LPG) which is occasionally used by low-and-middle-income HHs when these traditional fuels are not readily available. It may be argued that HHs may acquire firewood for cooking at no financial cost, however, this is not necessarily the case, as there is an indirect cost to be considered in the loss of earnings from alternative productive uses of time and effort to the task of collecting the firewood specifically for cooking.

The remainder of the paper is organized as follows; Section 2 outlines the methodology and the steps taken to determine the key factors to evaluate the least cost eCook scenario (considering both direct connected and (in-direct) battery-operated eCook). Section 3 presents the hybrid PV/diesel mini-grid characteristics used in this research study. Section 4 includes a brief introduction to the techno-economic modelling tools as well as the input assumptions and system constraints considered in each of the simulations. The results are presented and analysed in Sections 5 and 6, and the research conclusions are presented in Section 7.

2. Methodology

This paper presents the methodology and results of a techno-economic study to provide a comparative analysis of the cost of energy when cooking through a range of contextualized cooking scenarios—cooking only with conventional fuels (charcoal or firewood), with 100% eCook (direct electric cooking or through eCook batteries) as well as fuel stacking. The energy mix for fuel stacking and the ratio can vary from one HH to another depending on many factors. Additionally, there remains a lack of cooking data concerning consumer behaviour. Therefore, it is difficult to predict conclusively the energy mix ratio, which is why it is more practical to study a 50:50 ratio (eCook to conventional) to understand the future trends in costs. The results explore only a subset of possibilities for the energy cooking mix. The cooking scenarios are summarized in Figure 1. They intend to provide a clear understanding of the issues surrounding the barriers associated with an eCook transition in rural areas, particularly eCook batteries, and to give an indication of the key factors needed to reduce the cost of cooking with electricity.

From Figure 1 “Direct Electric Cooking” is split into two eCook scenarios:

- “Direct Electric Cooking #1—for PV/Upgrading Storage only/Diesel Hybrid”: evaluating the monthly energy cooking cost when upgrading only the centralized battery and the bi-directional converter. Upgrading the battery bank will permit storage of the surplus daily PV energy for later use by 47 HHs to cook all the daily meals with eCooks directly connected to the mini grid (the reason for only connecting 47 HH out of 108 HH to eCook is explained in Section 3).
- “Direct Electric Cooking #2—for PV/Storage/Diesel Hybrid”: determining the optimal hybrid PV/diesel mini-grid size (PV array, centralized battery, diesel generator, PV-inverter and bidirectional converter sizes), in addition to the monthly energy cooking cost to permit 47 HHs to cook all daily meals with eCooks directly connected to the power supply.

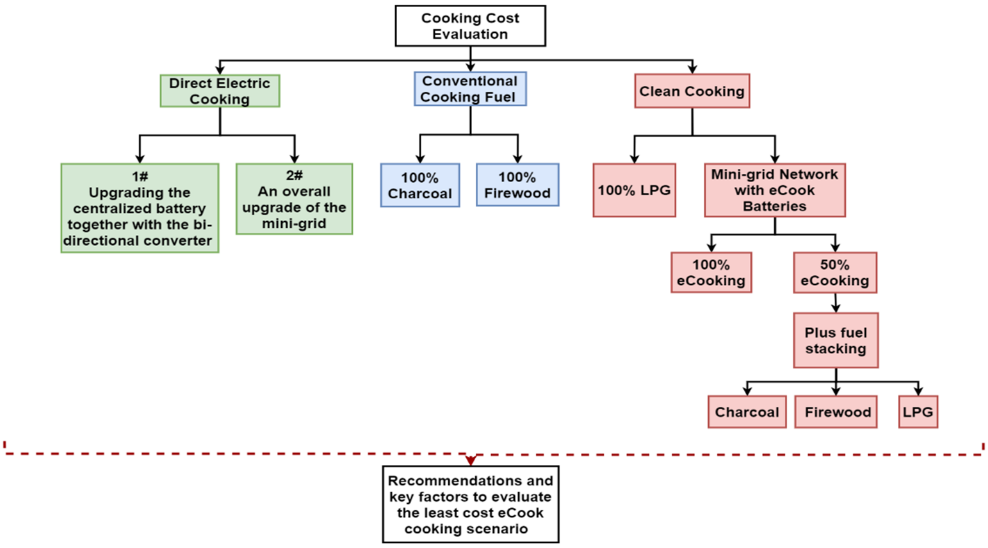

Figure 1. Contextualized cooking scenarios to evaluate the monthly cooking cost.

The "Conventional Cooking Fuel" scenario deals with HH cooking either with "100% Charcoal" or "100% Firewood". While the "Clean Cooking" scenario comprises five cooking scenarios, the first explores cooking with "100% LPG", the second one assumes that HHs switch to using battery-operated eCook where the cost is evaluated for 100% eCook, and the three scenarios developed when using 50% eCook with 50% of stacking fuel, the fuel used are charcoal, firewood and LPG.

For 100% eCook, the daily average cooking demand is 2.2 kWh which accounts for breakfast, lunch, and dinner, yet, to cook both breakfast and dinner there is a need for 1.6 kWh/day. As shown in [13], the latter was used to size the eCook battery, since it is only used in the morning and the evening, while the lunch demand is directly supplied by the mini-grid generation. The size of the battery calculated accounts for the worst-case scenario, where the minimum and maximum state of charge (SoC) are set at 20% and 80%, respectively. Additionally, 1.5 days of autonomy and other factors mentioned in [13] were included to improve the battery's performance through its mid-life design. Therefore, for the 100% eCook and the 50% eCook scenarios, 6 kWh battery and 2 kWh batteries are used, respectively, throughout the cost analysis of this paper.

It is important to mention that for the 100% eCook scenario, breakfast and lunch are cooked using a hotplate, while dinner is cooked on either or both a 1 kW hotplate and a 1 kW EPC [13]. For the 50% eCooking, only an EPC is used with fuel stacking.

The main findings lead the way, highlighting the key factors to bridge the affordability gap between firewood and eCook battery-based cooking. From this other cooking scenarios evolved, and subsequently simulated, assessed and compared alongside the "100% Firewood" cooking scenario cost when taking into account the non-market. The non-market value can be estimated and quantified by taking the value of unpaid labour for collecting firewood plus its social cost of carbon. In general terms, the cost of unpaid labour is valued by calculating the amount of time spent collecting the firewood and, the wage paid to casual employees and a person with similar skills employed in public or private sectors [3,18]. While the social cost of carbon is the total damage to the economy and human welfare created by one extra ton of CO_2 emissions, converted to dollars [19,20]. Using the results obtained from [3], the non-market value of firewood is estimated to range between 0.17/kg to USD 0.37/kg, where the cost corresponds to harvesting unsustainably from local forests.

The remainder of the paper gives a more detailed description of the steps considered in these studies and the main results and findings.

3. Overview of Hybrid PV/Diesel Mini-Grid Used in Study

For the eCook analysis, the hybrid PV/diesel mini-grid includes a 30 kWp PV, 25 kW PV-inverter, 27.6 kWh centralized battery, 8 kW converter and a 9 kW backup diesel generator. This was developed in [13,21] as a composite for systems designed and installed by practitioners and based on the mini-grid design methods available in the literature. More detail on the mini-grid design and the load profile (inc. baseload and eCook load) can be found in [21]. It connects 108 HHs to the mini grid to supply their baseload, while the daily surplus PV energy used to charge the eCook batteries enables 47 HHs (≈43% of total HHs) to cook breakfast and dinner with eCook batteries, whereas at midday, the PV power generation and the backup diesel generator are used. However, for direct eCook (i.e., where an electric cooking device with no battery storage is connected directly to the mini grid), the system capacity can accommodate approximately 20% eCook devices (22 HHs with eCook) and on a cloudy day, this decreases to 6% (7 HHs with eCook) due to the lower PV output.

To achieve and maintain consistency in the cost analysis, and to easily compare between the "Direct Electric Cooking" and "Clean Cooking" scenarios (Figure 1) only 47 HH out of 108 HH are connected to eCook devices.

4. Cooking Cost Modelling Tool

Throughout this paper two techno-economic tools are used, Homer-Pro Software 3.14.4 and an eCook Modelling Tool.

4.1. HOMER-Pro Software

HOMER-Pro (Hybrid Optimization Model for Electric Renewables) software [22] was used to conduct a techno-economic analysis of the various scenarios, using particular input assumptions where necessary and system constraints, to find the lowest cooking energy cost for the "Direct Electric Cooking" scenarios in Figure 1. The defined input data for the mini-grid model in HOMER is summarized in Table 1.

Table 1. Mini-grid component cost data [21].

Component	Initial Capital Cost	Replacement Cost	Lifetime
PV array size	406.25 $/kWp	406.25 $/kWp	25 years
Diesel generator	500 $/kW	500 $/kW	15,000 h
Lithium-ion battery	555 $/kWh	555 $/kWh	10 years
Converter	446.75 $/kW	446.75 $/kW	10 years
PV-inverter	286 $/kW	286 $/kW	15 years

The lifetime of the project is 20 years and the inflation rates and the nominal discount rates used were 6% and 10%, respectively, which are considered standard figures for business planning [23]. The annual fixed operational and maintenance (O and M) costs account for 2% of distribution capital expenditures (CAPEX) [24]. For the non-eCook demand (i.e., baseload demand) and eCook demand, the load profiles were modelled by a group of researchers from MECS using the CREST demand model [15,25].

4.2. eCook Modelling Tool

For the "Conventional Cooking Fuel" and the "Clean Cooking" scenarios in Figure 1, the techno-economic eCook modelling tool developed by Leach and Oduro [14,26] is used. It enables the user to estimate the monthly costs of cooking in various scenarios—when cooking only with conventional fuels (charcoal or firewood), LPG, or incorporating eCook with/without varying levels of fuel stacking. For the financial analysis, the cost is spread over 5 years, representing a more practical way of implementing eCook in the near term with a Pay-As-You-GO (PAYGO) business model, and with the discount rate set at 10%. The fuel cost range and the electricity tariff in Tables 2 and 3 were taken as a baseline based on the data published in [14,27]. The data shown in Table 2 highlights the most recent data collected from the cooking diary studies which tracked the energy use, cost and cooking practices of a total of 20 HHs in Tanzania, where the HHs are connected to a solar-hybrid mini-grid.

Table 2. Conventional fuel cost.

Charcoal ($/kWh)		Firewood ($/kWh)		LPG ($/kWh)	
Low	High	Low	High	Low	High
0.01	0.02	0.007	0.012	0.078	0.16

Table 3. Electricity tariff.

Mini-Grid Electricity Tariffs ($/kWh)		National Grid Tariff		
		Electricity Tariff		Lifeline Tariff * and Monthly Allowance
Low	High	Low	High	Lifeline tariff: $0.04/kWh
0.46	0.74	0.1	0.2	allowance: 75 kWh

* Lifeline tariff means that HHs are provided with a minimum unit of electricity per month at a low cost.

All of the scenarios conducted and shown in Figure 1 were first simulated with the national grid tariff and then with the mini-grid tariff to compare both cost trends and the impact of the high mini-grid tariff when moving towards eCook. It should be noted that the results in Section 5 assume that the wood is harvested sustainably, with replanting and regrowth, which justifies the low cost of firewood.

Furthermore, in this paper, the monthly cost of each scenario is calculated for the years 2022 and 2030. The techno-economic eCook modelling tool assumes that the eCook component costs are expected to reduce gradually over time, and the prices of traditional fuels are expected to increase (at 3% per year). For more detail on the eCook modelling tool refer to [18]. The analysis of each of the cooking scenario results is presented and discussed in Section 5.

5. Results and Analysis

From Table 4, in the "Direct Electric Cooking #1—with PV/Storage" scenario, a 345 kWh battery bank is required and 24.4 kW bi-directional converter, to store the surplus daily PV energy required to cook both breakfast and dinner.

Table 4. Proposed mini-grid component sizes to enable direct eCooking.

Scenarios	PV Array	Diesel Generator	Lithium-Ion Battery	Converter	PV-Inverter
	[kW]	[kW]	[kWh]	[kW]	[kW]
Direct Electric Cooking #1	30	9	345	24.4	25
Direct Electric Cooking #2	87.1	43	82.8	25	15

In this scenario, the required battery capacity is high as it is sized for 3 days of autonomy to try and meet most of the high early morning and evening cooking demand during extended periods of low solar resources. Any trade-offs in the availability of supply to reduce system costs are not considered in this study but could be in future. Another reason for the high levels of storage capacity is that the PV array and the backup diesel generator generation are limited (Table 4). This scenario suggests that HHs will pay USD 66.6/per month. Comparing this value to the cost of the "Direct Electric Cooking #2—with PV/Storage/Diesel" cooking scenario USD 38.94/month, it is considerably higher, which indicates that upgrading the centralized battery is not the most cost-effective solution.

In fact, for such systems, it would be more practical to install mini-grids that are sized appropriately from the outset to accommodate eCook, rather than upgrading the components later. Additionally, the battery cost is still considered a major barrier preventing the market breakthrough of battery-powered domestic products and appliances. In addition, for "Direct Electric Cooking #1" there remains a 1% annual energy demand which is not met by the available mini-grid generation.

Figure 2 shows the monthly cooking costs in USD based on the cooking scenarios in Figure 1. The first two involve cooking 100% with conventional fuels showing that both are available at a low cost; for 100% charcoal, the cost ranges between USD 8–17/month while 100% firewood is much less (USD 5–9/month). Moving towards clean cooking, cooking 100% with LPG becomes the best cost-competitive option (USD 11–22/month) compared to eCooking as it has the lowest cost. The results of 100% eCook, requiring a 6 kWh battery demonstrate that the monthly cost is the most expensive compared to the other cooking scenarios, which is seen as a cost barrier for low-and-middle-income HHs. However, a gradual transition towards eCook helps to reduce the size of the battery to 2 kWh along with the monthly cooking cost. Using a mix of 50% firewood with 50% eCook is seen as the most cost-effective of the three combinations of fuel stacking scenarios when the electricity source is either from the national grid or the mini-grid—with a cost of USD 24–26/month and USD 45–62/month, respectively. A mixture of 50% charcoal and 50% eCook is the second most cost-effective option with the cost of using the national grid-supplied electricity at USD 26–32/month compared with mini-grid-supplied electricity at USD 47–67/month. Pairing 50% eCook with 50% LPG instead of conventional fuels increases the cost to USD 28–35/month when using the national grid tariff and to USD 49–71/month when using the mini-grid tariff. The data shows that in an off-grid context characterized by a high cost of electricity, transitioning to eCooking with and without fuel stacking is more challenging. Hence, there is a need for further investments and policies that result in the cost reduction of mini-grid electricity prices to achieve greater parity with national grid-supplied electricity. By 2030, it is projected that the cost of firewood, charcoal and LPG will rise as illustrated in Figure 3; however, cooking with 100% firewood and stacking firewood with electricity remains the cheapest option. It cannot be ignored, however, that cooking with firewood leads to a high level of emissions if it is not harvested sustainably.

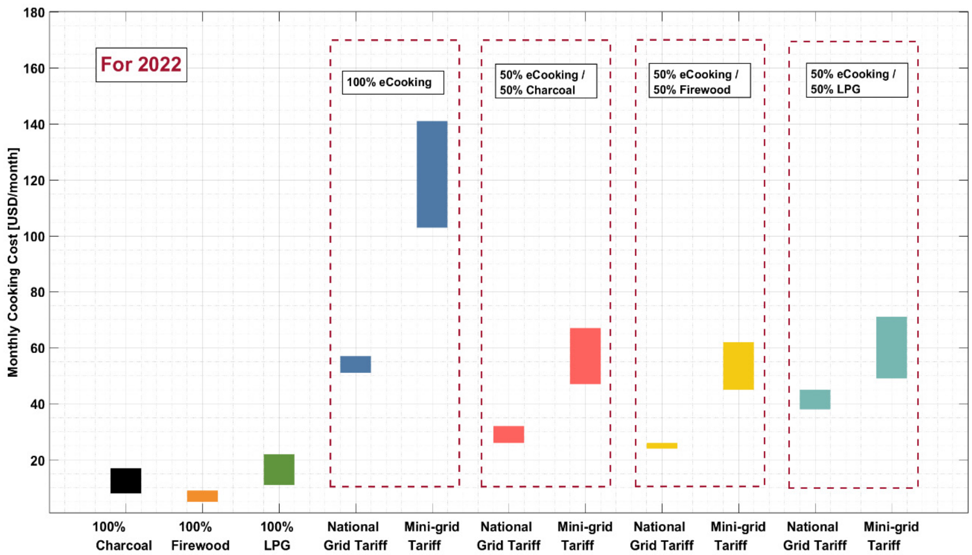

Figure 2. Monthly cooking cost of the contextualized cooking scenario under study calculated for 2022.

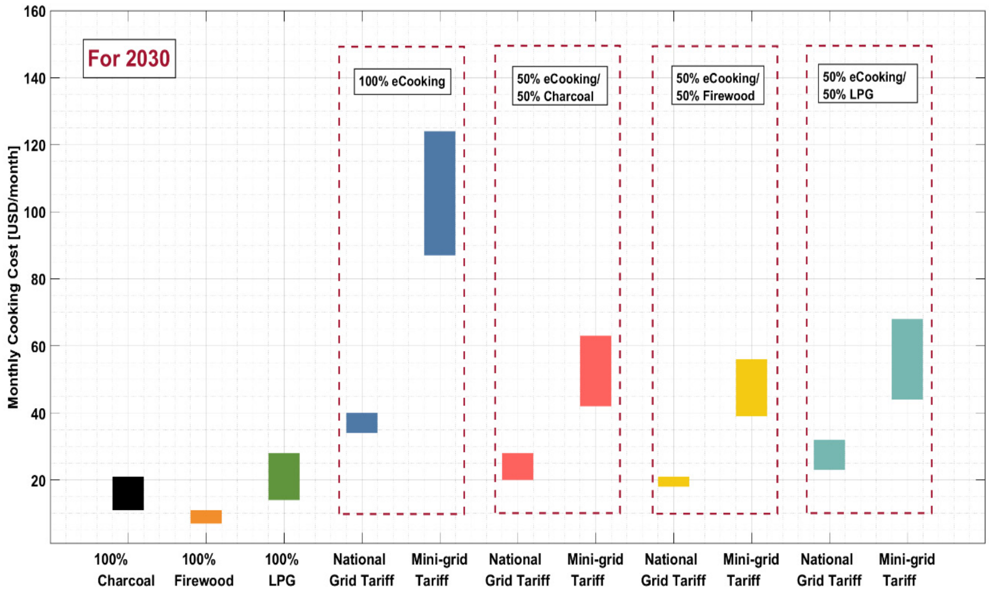

Figure 3. Monthly cooking cost of the contextualized cooking scenario under study calculated for 2030.

As previously mentioned, LPG presented itself as the cheapest option for clean fuels. The reason behind this is that some Governments offer microloans for the initial upfront costs of LPG equipment, subsidized refill costs and set transport costs for delivery to rural areas. However, there is still much scepticism by the public surrounding the safety concerns of LGP.

The main key findings from the analysis herein are:

- Cooking with firewood is the cheapest option, although at this stage of the analysis there is no commercial value included in the price of the firewood. Adding this to the estimated cost, as this becomes scarcer due to overharvesting and even due to climate change impacts, could significantly change the results.
- The battery size for 100% eCooking is costly, accounting for the most-costly scenario, as mentioned in Section 5. This leads directly to an increase in the initial investment cost as well as the monthly cooking cost. To further reduce the battery capacity, instead of sizing the eCook battery to account for a minimum SoC of 20% and a maximum SoC of 80%, it would be more practical to take a minimum and maximum SoC of 20% and 100%, respectively. Additionally, a one-day autonomy was selected instead of 1.5. This gives an eCook battery size of 3 kWh for 100% eCook and 1.25 kWh for 50% eCook (the implications of this term of cost is shown in Section 6).
- It is important to reduce the mini-grid tariff to a value close to the national grid tariff as well as to increase the lifeline tariff allowance to account for the eCook energy consumption.

The following section presents results that include a comparative analysis when incorporating these key points in the cooking cost evaluation.

6. Closing the Affordability Gap between Firewood and eCook Battery

6.1. Developed Scenarios to Bridge the Affordability Gap

This section intends to characterize the condition under which battery-based eCook can be more cost-efficient than firewood cooking and so addressing the affordability gap. As highlighted in Section 5, since firewood is the least expensive cooking fuel option used by most low-and-middle-income HHs, the target is for the cost of battery-based eCook to reach a level that is equal to or less expensive than firewood. Figures 4 and 5 examine the cost ranges of four different cooking scenarios.

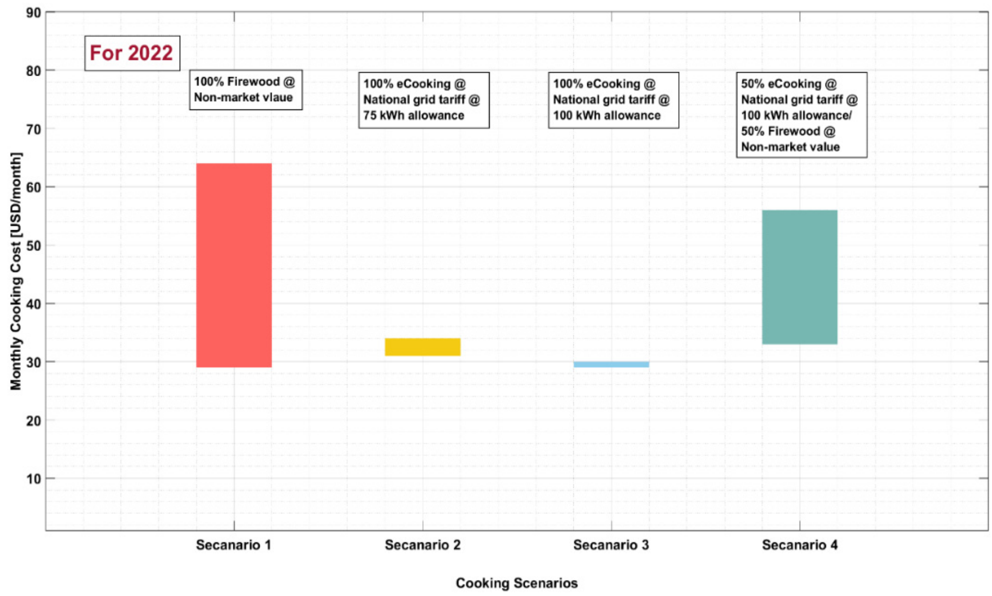

Figure 4. Monthly cooking cost of the contextualized cooking scenarios to close the affordability gap for 2022.

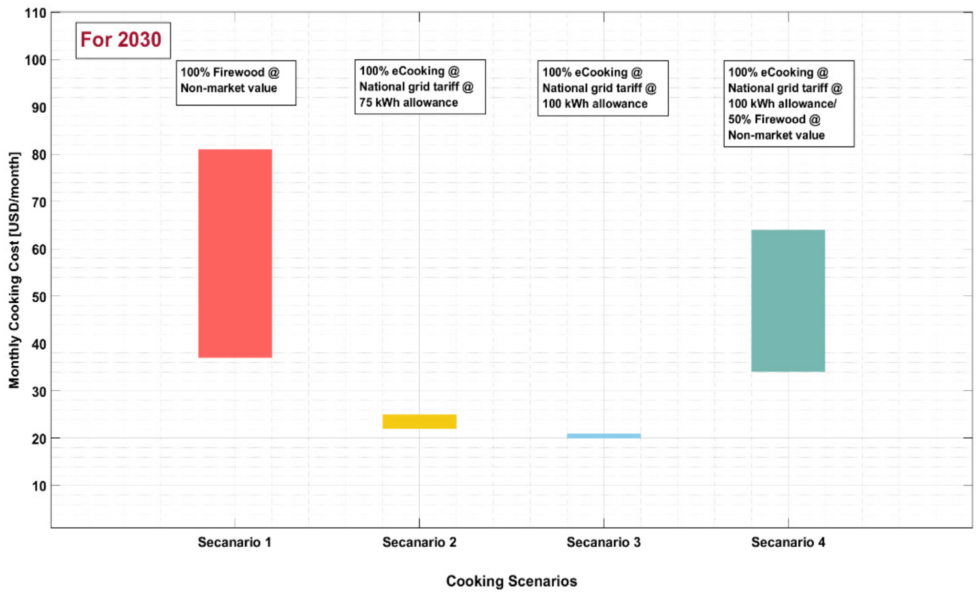

Figure 5. Monthly cooking cost of the contextualized cooking scenarios to close the affordability gap for 2030.

- Scenario 1: Here, cooking is done with 100% firewood and at this stage of the analysis the non-market cost is included which ranges between USD 0.17–0.37/kg this translates to USD 0.04 −0.086/kWh (when the wood is harvested unsustainably).
- Scenario 2: This explores the price of cooking with 100% eCook with a 3 kWh battery. The cost, in this case, was calculated using only the national grid tariff since in the previous results, it was seen that this was lower in cost than the mini-grid tariff.
- Scenario 3: This is the same as scenario 2, with an increase in the monthly allowance for the lifeline tariff from 75 kWh to 100 kWh with a lifeline tariff of USD 0.04/kWh.
- Scenario 4: The cooking price when using a mix of 50% eCook with a 1.25 kWh battery and 50% firewood. It also takes into account the non-market price of firewood and the 100 kW lifeline tariff allowance.

6.2. Result Analysis and Discussion

To compare the cooking costs for each of these scenarios the techno-economic analysis, the eCook modelling tool (introduced in Section 4) was used. From the results, the high cost occurs when cooking with firewood is inefficient and the full non-market cost (value of unpaid labour and environmental impact) of fuel is included. In this case, for 2022, the cost of cooking with firewood ranges between USD 29–64/month.

Nevertheless, 100% eCook is between USD 29–30/month for scenario 3. The overlapping bars in Figure 4 imply that there could be an opportunity for parity when the firewood cost reaches USD 29/month if, (1) the battery cost is affordable, (2) there is an increase in the lifeline allowance and (3) the non-market price of firewood is taken into consideration. The same applies to the cooking prediction costs for 2030. Additionally, the 100% eCook cost of scenario 3 is reduced further to USD 20–21/month. However, if the firewood is harvested sustainably, ensuring it is high in quality and dry, it would be difficult for battery eCook to compete (see Section 5). Under the fuel stacking scenario (50% eCook and 50% firewood) for both 2022 and 2030, scenario 4 becomes the least favoured option compared to scenarios 2 and 3 when the non-market value is included in the firewood cost.

Including these factors in the techno-economic cost modelling widens the opportunity for affordable eCook with respect to firewood usage. For mini grids with high tariff prices pro-poor actions should be encouraged to follow tariff schemes that help and make the connection and operational costs affordable to end-users, and/or focus on the investment costs of the system to support the poorer rural areas in accessing modern energy services. The national grid's tariff scheme could be a suitable option, known as the graded tariff regime, which is based on two tariff rates: a low tariff for the first kWh and a higher tariff for higher consumption. To access eCook services, it is essential for the mini-grid tariff rates to be coherent with the national level and to increase the lifeline tariff allowance sufficiently, to cook above the baseload energy demand while being affordable to all at the same time. Due to different factors, tariff rates range considerably from country to country across Sub-Saharan Africa. For example, Zambia has a relatively attractive graded tariff scheme with a high tariff of USD 0.09/kWh and a lifeline tariff of USD 0.02/kWh for a monthly allowance of 200 kWh. The same can be seen in Kenya in terms of the lifeline tariff allowance ($0.17/kWh for monthly consumption of 100 kWh), although the high tariff is USD 0.23/kWh. In the case of Tanzania, there is necessary to increase the monthly allowance limit from 75 kWh to 100 kWh or even more, to enable 100% eCooking (as shown in this paper). However, Uganda's graded tariff scheme could present challenges towards switching to eCook due to its relatively high tariff of USD 0.2/kWh and lifeline tariff of USD 0.06/kWh for a 15 kWh monthly allowance. Comparing these countries' tariff rates, clearly shows that a more structured pricing scheme is necessary to provide an optimal low tariff and a more generous allowance, sufficient to make mini-grid projects commercially viable. In addition, further Governmental subsidies, support grants and incentives from foreign aid and/or international development organizations are needed to make the expansion of mini grids in Sub-Saharan Africa more attractive to developers.

The wood collected in rural areas is a commodity without a market value, as the firewood is sourced from public forests and there are no monetary transactions involved. However, there is a non-market labour value and social carbon cost attached to this operation. There are gender inequality implications to consider also, as it is predominantly women and children who collect this essential HH commodity and in doing so are prevented from receiving education, training, lost childhood, and social activities as well as endangering their physical health, including the suffering of back injuries caused by carrying heavy loads and respiratory illnesses caused by inhalation of toxic fumes when cooking indoors, leading to 4 million premature deaths annually. These non-market labour activities and the social return on investment must be factored into the price of the firewood. In addition, populations must be taught the risk factors involved and shown the benefits of clean cooking and using electricity. It is necessary to develop an appropriate methodology and implement it as an important functional tool to estimate the non-market cost of cooking.

The outset could be by conducting surveys across the Sub-Saharan countries capturing a wider variety of data, including evaluating the amount of time spent collecting firewood and, the wage paid to casual employees and a person of similar skills employed in the public or private sectors, together with the social cost of the carbon footprint. Analysing the data could compare the similarities and differences of the individual countries surveyed, predicting the optimal non-market value and evaluating whether it is appropriate to deploy eCook in that particular country or consider another type of clean cooking.

7. Conclusions

To achieve widespread uptake, eCook-supported batteries must be seen as accessible and highly desirable products by the low-and-middle-income HHs. From the analyses in this paper, it is apparent that 100% eCook becomes cost-competitive with firewood when including these three main factors: (1) accounting for the non-market cost of firewood, (2) ensuring a low mini-grid tariff that is in a range of the national grid tariff, (3) an optimal eCook battery capacity sufficient to meet the required demand.

However, when these factors are considered, with a HH monthly salary of USD 25–30, cooking with eCook batteries is clearly still uneconomical and impracticable.

The effects of climate change are experienced each year in Sub-Saharan Africa in the form of drought, flooding, and migration of people to survive these environmental impacts. Although research, at present, is very limited on how these affect the supply and price of wood for cooking and wood fuel, there are likely to be increasing consequences and shortages, inevitably leading to an increase in the price, putting a strain on low-income families by increasing the cost of cooking and heating, and additional collection times—quite apart from the environmental degradation and biodiversity loss caused.

Furthermore, regulations should be implemented by proposing to create plantations for firewood and impose controlled kilns for producing charcoal, reducing deforestation and unnecessary CO_2 emissions created from old or damaged private kilns. The operators would be required to obtain permits and pay tax revenues to the relevant governments. This additional income through carbon credit could then be invested, specifically in renewable energy projects, primarily in rural areas, to install solar PV panels, improve the country's infrastructure or subsidize the price of batteries or electricity. This can be regarded as a step towards making eCook on mini-grids viable and be adopted by other developing countries.

Another area to explore, to reduce the energy cost, is to examine the advantages/disadvantages of a combination of energy resources in mini-grids and compare them with hybrid solar mini-grids. The advantages and benefits of different technologies increase the share of renewables, covering a variety of shifting load profiles during the day and reducing the cost of energy. Nevertheless, three key factors must be considered when assessing the hybrid-multi source mini-grids:

- The renewable resources and the technologies available in the region under study
- The structural cost of the system
- The quality of service

The consequence when sizing the eCook battery may be under/oversizing the battery, the former could lead to the cooking demand not being met, while for the latter, the battery size could be detrimental to the system's cost. Scalable cooking with electricity is still in an embryonic stage and there remains a lack of cooking load profile data and consumer behaviour data. Additionally, most of the data available was collected over a short period, making it difficult to predict the long-term effects or to extract meaningful information on day to day and seasonal variations as well as battery performance. Therefore, there is a need to conduct further eCook battery trials on mini-grids to identify research gaps in selecting the appropriate key factors for the battery, calculate the optimal size with a balancing performance, lifetime, cost within necessary safety limits and meet all the cooking demands on days and locations with variable levels of solar resource.

ECook batteries offer a potential solution to clean cooking, however, a full life cycle assessment is needed to establish the environmental benefit of this transition and compare case-by-case the environmental effects of the cooking scenarios studied in this paper. Another area for further research, not discussed here, is the impact of increasing the load factor of the min-grid with the cost of energy, as demand for cooking could increase and generate additional income for the developer and operator. These will be the subjects for future research.

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Abbreviations

CAPEX	Capital Expenditure
DSM	Demand Side Management
EBMS	ECook Battery Management System
eCook	Electrical Cooking Appliance
EPC	Electric Pressure Cooker
HH	Household
LPG	Liquid Petroleum Gas
MECS	Modern Energy Cooking Services
NPC	Net Present Cost
PV	Photovoltaic
SoC	State of Charge

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