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Solar electric cooking in Africa: Where will the transition happen first?☆

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ABSTRACT

Whilst the rapid spread of solar photovoltaics (PV) across Africa has already transformed millions of lives, it has yet to have an impact on the main energy need of poor households: cooking. In the context of falling global PV prices, recent advancements in battery technology and rising charcoal/fuelwood prices in severely deforested regions, the door is opening for a potentially transformative alternative – solar electric cooking (PV-eCook). While initial investigations focused on solar home systems sized for cooking (cooking device, battery storage, charge controller and PV array), it has since been shown that battery-supported electric cooking (eCook) can also strengthen national, mini, micro and nano grids. This paper presents a multi-criteria decision analysis (MCDA) based methodology, accounting for a wide variety of socio-cultural, political, technical and economic factors which are expected to affect the uptake and potential impact of eCook across a variety of African contexts. It shows the concept has considerable viability in many African countries, that there are significant sizeable markets (millions of potential users), and that within the next five years the anticipated costs of eCook are highly competitive against existing 'commercialised polluting fuels'.

1. Background

Approximately 3 billion people use biomass for cooking [1]. This pervasive use of solid fuels – including wood, coal, straw, and dung – with traditional cookstoves results in high levels of household (HH) air pollution, extensive daily drudgery to collect fuels and manage fires, and serious health impacts. Smoke from cooking indoors with biomass is associated with a number of diseases, including acute respiratory illnesses, cataracts, heart disease and even cancer [2,3]. Women and children are most frequently exposed to indoor cooking smoke in the form of small particulates up to 20 times higher than the maximum levels recommended by the World Health Organization (WHO). It is estimated that smoke from cooking fuels accounts for nearly 4 million premature deaths annually worldwide.[1]

Greenhouse gas emissions from nonrenewable wood fuels alone total a gigaton of CO_2e per year (1.9–2.3% of global emissions) [4]. The short-lived climate pollutant black carbon, which results from incomplete combustion, is estimated to contribute the equivalent of 25–50% of carbon dioxide warming globally – residential solid fuel burning accounts for up to 25% of global black carbon emissions [5]. Up to 34% of woodfuel harvested is unsustainable, contributing to climate change and local forest degradation. In addition, approximately 275 million people live in woodfuel depletion 'hotspots' – concentrated in South Asia and East Africa – where most demand is unsustainable [4].

It is well known that open fires and primitive stoves are inefficient ways of converting energy into heat for cooking. While there has been considerable investment in improving the use of energy for cooking, the emphasis so far has been on improving the energy conversion efficiency of biomass via the development and marketing of Improved Cookstoves (ICS/ICs). Indeed, the foreword to a recent overview of the state of the art in ICS [1] aspires to a world where this situation changes but notes that the use of biomass for cooking is likely to continue to dominate through to 2030 due to population growth, a conclusion shared by the

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[1] More than the deaths from malaria and tuberculosis combined. Moreover, UNICEF [63] highlighted that as many as 1 in 10 deaths, or 600,000 per year, of children under five years old was attributed to this form of pollution.

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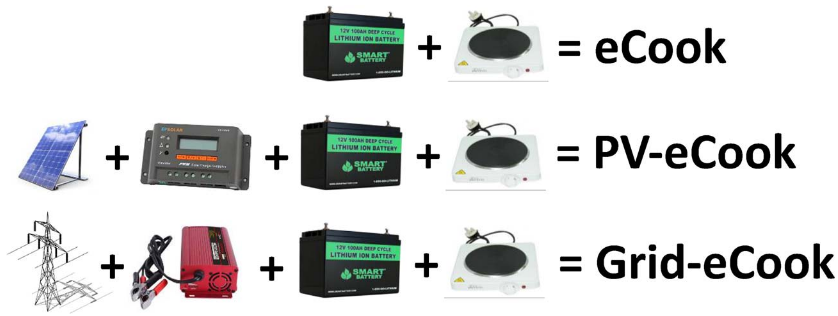

Fig. 1. Pictorial definitions of 'eCook' terminology used in this paper.

IEA[2]/World Bank SE4All[3] [6] GTF.[4]

They state that "the 'business-as-usual' scenario for the sector is encouraging but will fall far short of potential" ([6], p. 9). They note that with current trends, globally over 180 million households will gain access to, at least, minimally improved cooking solutions by the end of the decade. However, 'business-as-usual' will still leave over one-half (57%) of the developing world's population without access to clean cooking in 2020, and 38% without even minimally improved cooking solutions. Even more worryingly, this existing scenario still depends considerably upon transitions to ICS (where emissions, whilst reduced, remain high) [7] or liquid fuels like kerosene. The damaging health implications of the latter are increasingly being recognised, leading the WHO to create a new classification of 'polluting fuels', which includes solid fuels plus kerosene [8]. The report also states that the uptake of 'cleaner' stoves is barely affecting health outcomes, and that only those with forced gasification make a significant improvement to health.

There is an emerging body of literature which calls for much greater reflexivity in attempting to understand why, despite all of the assumed benefits of clean cookstoves and the considerable expenditure on promoting them, the results appear to be so disappointing. Khandelwal et al. ([9], p. 1) conclude that "Rural women do not prioritise ICs, but addressing their priorities requires either capital-intensive investment or challenging powerful institutions. In contrast, IC interventions are relatively cheap, decentralised, mechanical and seemingly apolitical, hence their popularity in development programmes." Existing investment in the promotion of ICS typically begins with the mechanisms to distribute new and supposedly improved technology, rather than understanding the cooking practices of those being encouraged to adopt it. Consequently, access to cleaner cooking solutions alone is clearly not translating into sustained new patterns of cooking [10]. This has led to recent calls for greater attention to be paid to the ethnography of 'mundane bioenergy', the questions of how and why "families burn wood, dung, charcoal, and crop residue in cookstoves for their subsistence needs" ([11], p. 1).

Finally, where traditional biomass fuels are used either collected in rural areas or purchased in peri urban and urban conurbations, they are a significant economic burden on households either in the form of time or expenditure. McKinsey Global Institute [12][5] outlines that much of women's unpaid work hours are spent on fuel collection and cooking. The report explores the economic potential available if the global gender gap were to be closed. The findings show that if women and men fully participate in the labor market, as much as $28 trillion, or 26%, could be added to the global annual GDP in 2025. Access to modern energy services could redress some of this imbalance and release time into the labor market.

Against this backdrop, there is surely a need to try a different approach aimed at accelerating the uptake of 'clean' cooking. Sustainable Development Goal 7 (SDG7) calls for the world to "ensure access to affordable, reliable, sustainable and modern energy **for all**" ([13], p. 1). Despite the combined international commitment to both increasing access to electricity and reducing dependence on biomass cooking, policy and private sector actors are treating these challenges as two separate, unrelated problems. Both of which are seen as requiring a completely new transformative strategy if they are to stand any chance of being addressed effectively within the timescales contemplated. In this paper, we explore how the use of battery-supported electricity for **cooking** could meet the twin goals of both increasing access to electricity and providing truly clean cooking to households in developing countries.

2. Introduction to eCook

In the context of falling global PV prices, recent advancements in battery technology and rising charcoal/fuelwood prices in severely deforested regions, the door is opening for a potentially transformative alternative: battery-supported electric cooking, or eCook [14–18]. Initial investigations focused on a configuration comparable to the popular Solar Home System (SHS), referred to here as PV-eCook, and consisting of a cooking device, battery storage, charge controller and PV array. It has since been shown that using a battery charger and battery to support cooking appliances during blackouts in a similar way to a UPS (Uninterruptable Power Supply) could also strengthen unreliable national, mini-, micro- and nano-grids. For grid operators, it could also offer a form of demand side management and/or create additional revenue [18]. This variant is referred to as Grid-eCook, but is not explored in detail in this article given our focus on solar PV. Fig. 1 shows the key system components that define the three terms used throughout this paper: eCook, PV-eCook and Grid-eCook.

The speed and degree to which this concept is taken up is expected to vary widely across this culturally and physically diverse continent, however its potential impact is considerable. eCook systems could play a major role in meeting SDG 7; largely by facilitating access to affordable, reliable, sustainable modern energy for all in relation to cooking.

The concept of PV-eCook has been possible since the advent of solar photovoltaic panels. With enough panels and large enough batteries, a system could deliver enough energy for cooking for a HH. However, until recently, such a device would have been unrealistically expensive for families across the developing world. A typical mention of the concept can be found in UNHCR [19], which notes that it is feasible but dismisses it as prohibitively expensive. However, continued falls in the price of the two main cost components, PV and batteries, over the last decade mean that a solar PV based eCook system could be cost effective in some markets as early as 2019, an opportunity that is now being recognised by other researchers [20,21].

Batchelor [14] noted the ongoing price falls and proposed that HH systems could be developed such that by 2020 they might have a discounted monthly cost of $12 a month – an amount that over 1 billion

[2] International Energy Agency.
[3] Sustainable Energy for All.
[4] Global Tracking Framework.
[5] The power of parity: How advancing women's equality can add $12 trillion to global growth, McKinsey Global Institute [12].

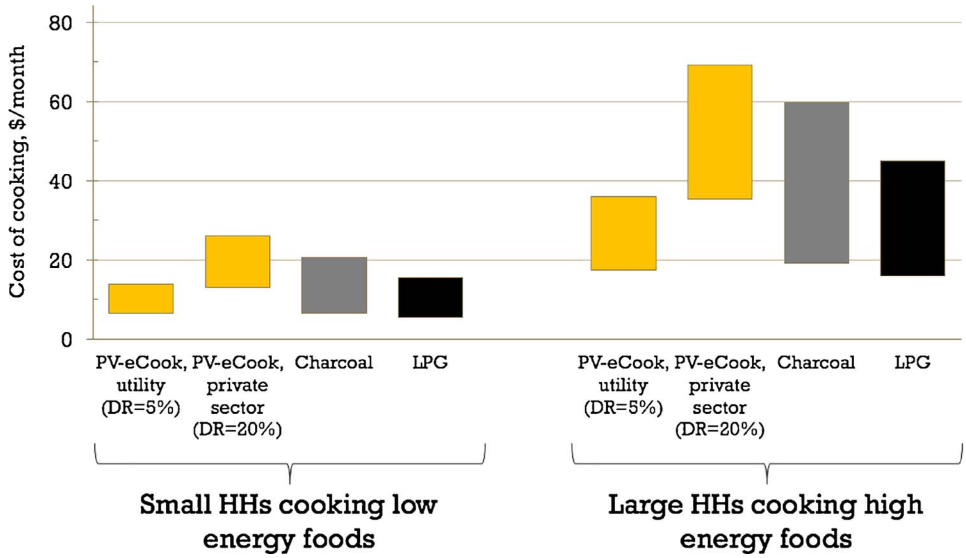

Fig. 2. Leach & Oduro's [16] techno-economic modelling results, showing the crossover point in 2020, where it is predicted to become cost-effective for a significant number of HHs to transition to PV-eCook.

people already regularly spend more than on their polluting fuel purchases. Leach & Oduro [16] modelled the concept for SHS, and compared the resulting energy with that 'delivered to the pot' by charcoal and LPG. Their modelling included a range of possible system efficiencies and component costs; and assumptions on the solar resource and culturally distinct cooking practices, resulting in bands of predicted monthly costs. Fig. 2 shows that although offset in 2015, by 2020 the bands of monthly costs for cooking with PV-eCook overlapped considerably with bands representing expenditure on conventional fuels, implying that it would be cost effective for HHs in this overlapping region to adopt PV-eCook by 2020.

Since then, recent papers such as Kittner et al. [22] have shown that the rapid learning curve in battery manufacturing has resulted in battery prices already dropping faster than expected. While Leach & Oduro [16], reasonably estimated the ex-factory price of LiFePO4[6] batteries would be between $200 and $300 per kWh storage by 2020, Kittner et al. [22] shows that they should reach $200 per kWh by 2019. This suggests that PV-eCook will be even more viable by 2020 than predicted.

What is more, whilst Leach & Oduro's [16] modelling included a range of system sizes from 2.2 kWh battery storage and 350 W PV up to, 9.8 kWh storage and 1300 W PV, subsequent research has shown that much smaller systems could be possible using energy efficient appliances. For example, rice for 4 people can be cooked in a rice cooker with under 0.2 kWh, therefore a small HH cooking rice as their main staple could upgrade their 0.2 kWh, 40 W SHS sized for lighting, TV and mobile phone charging could upgrade the system to PV-eCook by trading in their SHS for a 0.4 kWh battery and a 100 W PV panel.[7] The methodologies described in the *'Further Work'* section at the end of this paper aim to shed further light on what, how and when people cook in different cultures to enable the dimensioning of battery banks that can offer people affordable eCook solutions tailored to the way they cook.

eCook is fundamentally an economic proposition – that monthly/weekly/daily repayments on a battery-supported electric cooker could be comparable to current expenditures on HH cooking fuels. Firewood, dung and crop waste are usually collected and therefore there is not normally an existing expenditure. Whilst time spent collecting fuels can in theory be converted into new income, in practice new income generating opportunities are often limited, especially in rural areas where collectable fuels are most available, making users of these fuels harder to reach. In contrast, in most contexts, kerosene, charcoal and coal are commercialised. As a result, this study seeks to determine how many people are using these 'commercialised polluting fuels', where they are located and how much they are paying for them, as they represent the greatest opportunity to divert an existing expenditure to improve quality of life.

We extend the analysis to include LPG, which is significantly cleaner than 'polluting fuels' and has an important role to play as a transition fuel, however as a fossil fuel it does not offer a truly sustainable long-term pathway to clean cooking [21]. It can easily be compressed, facilitating distribution, allowing it to reach far beyond the limits of the piped networks in which natural gas is distributed. However, it is a finite resource and still contributes to climate change. Argus Consulting [23] note that the development of hydraulic fracturing enabled the exploitation of shale gas that was previously uneconomically recoverable. As a result, the world is currently 'LPG long', as it is co-produced alongside other petroleum products that are in higher demand. Consequently, Argus Consulting [23] predict continually falling global LPG prices until 2020, followed by a return to 2010 levels by 2026.

Like most renewable energy systems, considerable upfront investment is required in terms of capital expenditure. Leach and Oduro's model presents the system cost as a levelised monthly expenditure, with initial investment and ongoing maintenance discounted over the system lifetime, to enable comparison with current expenditure on charcoal and LPG. Whilst ICS have struggled to find an appropriate business model, pay-as-you-go solutions for solar lighting have facilitated rapid uptake [24]. Pay-as-you-go for eCook would enable direct substitution of weekly charcoal expenditure and a reframing of the concept not as an ICS but as a repurposing of household expenditure to support the roll out of electrical infrastructure and associated services, which could therefore attract private and government investment in a way that ICS have not.

The other important behavioural factor that has the potential to be either a driver or a barrier to uptake, is fuel stacking. This is a well-documented phenomena [25–28,1], whereby people rarely move exclusively from a polluting fuel to a less polluting fuel. Rather they start to use the 'new' fuel, and revert to their old appliances and fuels for

[6] Lithium Iron Phosphate.

[7] This would allow them to cook rice twice a day (once during the daytime with most of the power coming directly from PV and once during darkness totally from the battery) plus have enough left over for lighting, TV and phone charging in the evening. If they wanted to cook all their food and heat all their water using energy efficient appliances such as insulated electric pressure cookers and therma-pots (insulated kettles), a 0.8 kWh, 200 W should be sufficient to cook 2 meals a day and reheat a third.

reasons such as shortages of the new fuel, cooking particular dishes, using smoke as an insect repellent or simply to have more pots cooking simultaneously. Whilst this clearly has health and environmental implications if occurring regularly, fuel stacking could be a vital enabler to address the limited battery capacity of eCook systems in the same way as petrol/diesel hybrids extends the range of electric vehicles and petrol/diesel generators can back up renewable power systems.[8]

eCook offers an equitable solution to clean cooking that can enable a smooth transition for the off-grid HH cooking on polluting fuels, regardless of whether the grid ever arrives, and if it does, whether it is reliable enough to cook on. Equally, if the same HH follows the ever accelerating trend of urbanization and relocates to an urban slum, eCook can repurpose their expenditure on polluting fuels to justify the extension of the grid, which may be just meters away, to their HH, regardless of how unreliable the connection may be once it is made. What is more, the development of either Grid- or PV-eCook paves the way for the other by developing supply chains, increasing awareness and progressing understanding of the compatibility of local cooking practices with electricity and batteries.

However, while there are many other potential aspects to eCook that could be discussed, within the confines of this paper we focus on the potential markets for PV-eCook, evaluating the readiness of African countries for such a potentially transformative range of systems and appliances. We state clearly – what was once seen as an unrealistic dream just a few years ago, could in fact be a game changer in the very near future, bringing modern cooking infrastructure and energy to all.

3. Aims, objectives and structure of the paper

This paper forms part of a broader programme of work that began with Batchelor's [14] proposition that by 2020, the monthly cost of cooking on a solar home system would be comparable with current expenditures on charcoal (the concept referred to here as PV-eCook). In 2015, the UK DfID[9] commissioned three studies to test the validity of the proposition from technical, economic and behavioural change points of view [15–17]. Batchelor's [18] synthesis of these three independent studies concludes that the initial proposition is worthy of further investigation, i.e. that by 2020 PV-eCook is likely to be a viable option for a significant number of poorer HHs.

The aim of this study is to contextualise the generic market characterisation and economic modelling carried out by Brown & Sumanik-Leary [15] and Leach & Oduro [16] to answer the following research question:

Where is the uptake of PV-eCook likely to occur first and where can it have the biggest impact?

By locating and quantifying the most viable and highest impact markets for PV-eCook, future research and implementation can be focussed on these contexts. To achieve this aim, the following objectives are defined for this study:

- Operationalise Brown & Sumanik-Leary [15] and Leach & Oduro's [16] generic research to compare specific national contexts.
- Quantitatively evaluate the viability and market size for PV-eCook in all relevant national contexts.
- Contextualise the statistics by presenting a qualitative evaluation of the opportunity for PV-eCook in the countries predicted to have the highest viability.

[8] For example, should all the relatives descend on a special occasion and a whole goat needs to be roasted, an eCook system sized to address the daily needs of the HH can easily be expanded by using old fuels and appliances to address this temporary need. To minimise health implications, an eCook-LPG hybrid system could be developed for minimal extra upfront cost and offer users more flexibility to balance cost with convenience.

[9] United Kingdom Department for International Development.

This paper presents a Multi Criteria Decision Analysis (MCDA) methodology, which independently evaluates each of the factors predicted by Brown & Sumanik-Leary [15] to affect the viability of PV-eCook in different contexts. All Sub-Saharan African (SSA) nations are then ranked by viability to predict where PV-eCook is likely to take off first. Further analyses are then presented to quantify the size of the market in each nation and when the price tipping point between PV-eCook and the key commercialised polluting fuels in use today is likely to occur. Finally, a qualitative analysis of the three countries with highest viability scores is presented.

4. Methodology

4.1. Theoretical framework

Conceptually eCook is a technological solution to a social problem – the lack of access to electricity and clean cooking facilities. Consequently, this research takes a social-technical systems[10] approach [29] to understand both the "social 'software'" and "technical 'hardware'" ([30], p. 1534). This socio-technical lens gives equal importance to the roles of technicians, politicians and end users as the functionality of solar panels, cooking appliances and batteries [30] and facilitates the disentangling of the intertwined social, cultural, political, technical, environmental, economic and other categorisations of factors that are likely to accelerate or constrain the uptake of eCook across the diverse range of national contexts that exist in the world today.

4.2. Multi-criteria decision analysis (MCDA) techniques

This study begins with Brown et al.'s [31] detailed exploration of the characteristics of eCook in comparison to the most widely adopted cooking technologies today. Their analysis identified the key contextual factors that characterise the places where eCook is likely to reach scale most rapidly. Alsop et al.'s [32] methodological approach of applying MCDA techniques to renewable energy for development market assessments, operationalises Brown et al.'s [31] framework to quantitatively compare the viability of eCook across national contexts through the assembly and analysis of the eCook Global Market Assessment (GMA) Database. The database was constructed in Microsoft Excel and is available for download as an open access resource from PV-eCook.org. It is hoped that the eCook GMA database will continue to evolve as more data become available and as more insight is gained into the factors that enable and constrain eCook in different country contexts. The authors welcome contact from interested readers who have new datasets and/or insight to share.

The nation state was selected as the resolution of this global analysis as there are a wide variety of publicly available quantitative data sets that have been constructed using standardized methodologies. The majority of these data sets are regularly updated, enabling the GMA to be brought up to date as and when required.[11] Where no such data sets existed (e.g. charcoal prices), additional research was carried out to acquire the necessary data (see Appendix A). Fig. 3 lists the key techniques employed to collect, process and analyse the data in the eCook GMA database assembled during this study.

Indicators were defined to measure each of the critical success factors identified by Brown et al. [31], as shown in Appendix B. More detail on each of the indicators, including an evaluation of their relevance to eCook, specific data processing techniques and the limitations imposed by the available data can be found in the eCook GMA Database. Weightings were assigned to each indicator, factor and category to control their relative influence over the final result.

[10] Also known as the social science systems approach.

[11] With a recommendation of a minimum of once every 4 years to reflect election cycles and potential policy changes, as well as significant shifts in fuel markets.

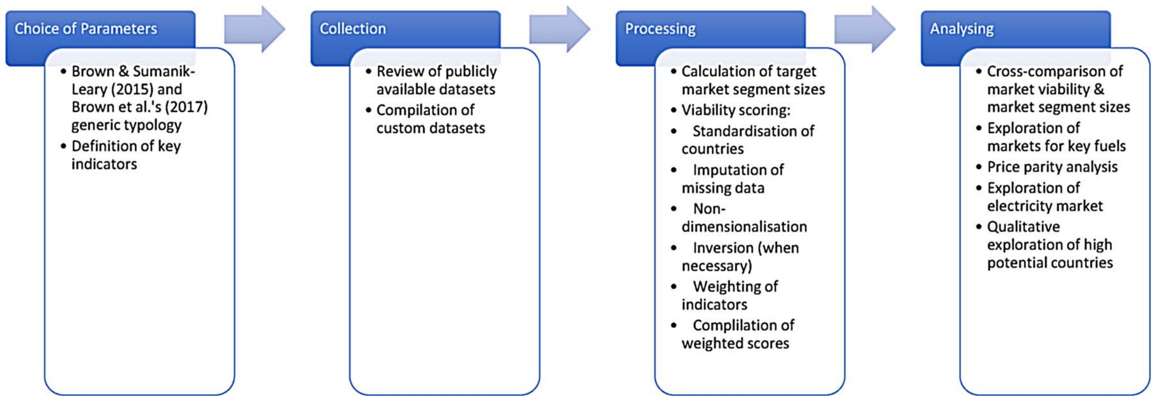

Fig. 3. Flow diagram listing data collection, processing and analysis methodologies.

In brief, the most critical factors influencing local market conditions for PV-eCook were identified as:

- Infrastructure
  - How easy will it be to obtain the key components for eCook initially through importation, but ideally by local manufacturing?
  - Is there a well-established SHS industry to pave the way?
  - How many off-grid rural HHs are there?
- Culture
  - What do people cook and how?
- Human
  - How challenging will it be for private sector to bring eCook to market?
  - What relevant skills are available locally?
  - Are women empowered and therefore able to drive this transition forward?
  - How stable is national governance and how favourable is their energy policy?
- Physical
  - How favourable is the local climate (solar resource and ambient temperatures) to generating solar electricity and storing it in batteries?
  - How severe is deforestation due to HH woodfuel harvesting?
- Economics
  - Which financing options are available to users and developers[12]?
  - How much does electricity, kerosene, charcoal and LPG cost and how many people cook with each?

Simple Multi-Attribute Rating Technique (SMART) [33] was selected as the most appropriate MCDA technique for this study, as it is simple to understand and is relatively streamlined (it only requires one decision to be made per indicator, sub-category and category). The SMART technique requires the decision maker to assign a weight to each indicator in descending order of influence, using the most influential indicator as a reference point with an assigned weight of 100. The process is then repeated for sub-categories, then categories and finally, the cumulative weights are multiplied by the scores for each indicator and summed to achieve a final overall score for each country. The reliability of the results of the study depend on minimising the individual bias imposed by those carrying out the weighting process. To allow sufficient debate around the relative influence of each factor to take place, weighting was carried out during an in-person focus group (the results of which can be seen in Fig. 4), comprising eCook consortium members from Gamos, University of Surrey and Loughborough University, with over 15 years' cumulative experience of research on eCook.

[12] Both in terms of income, access to innovative payment mechanisms (e.g. mobile money) and ability/cost to borrow the upfront capital.

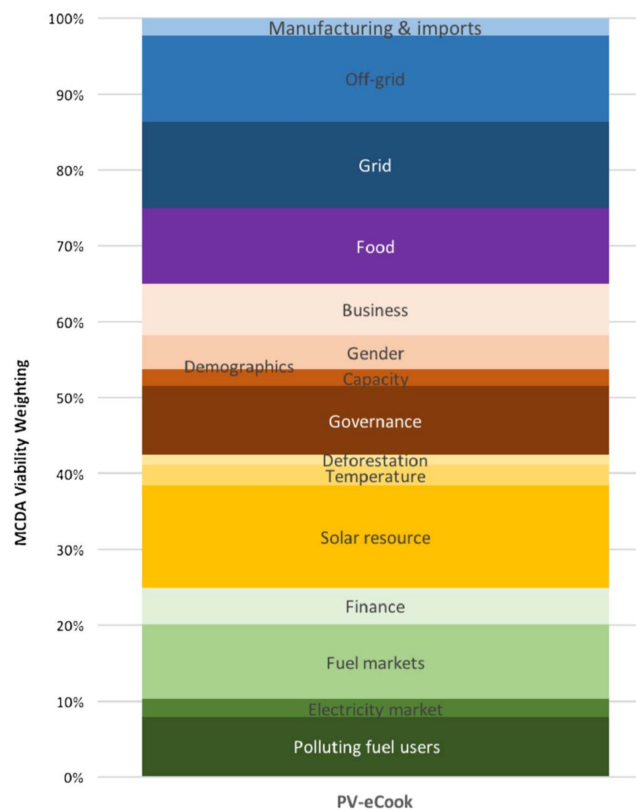

Fig. 4. Cumulative weightings for each factor under the PV-eCook weighting set (see Appendix C for comparison with Grid-eCook weighting set).

4.3. Limitations of MCDA approach

The weighting process will always introduce bias into the analysis, no matter how rigorously it is conducted. As a result, the weighting sets in the eCook GMA Database are editable and readers are invited to use their own judgement to edit the weightings and observe the impact this has on the viability scores. The detailed national market assessments described in the 'Further work' sub-section at the end of this paper will introduce a whole new range of experts to the eCook concept. This additional expertise should be leveraged to refine this study through the incorporation of new factors, by finding better ways of measuring the existing factors and by incorporating their opinions into updated weighting sets.

What is more, no data sets covered all the countries in the enquiry. If multiple data sets were available, they were collated to triangulate the findings and fill in any missing data points. An imputation process was used to complete the data sets by filling in any remaining gaps

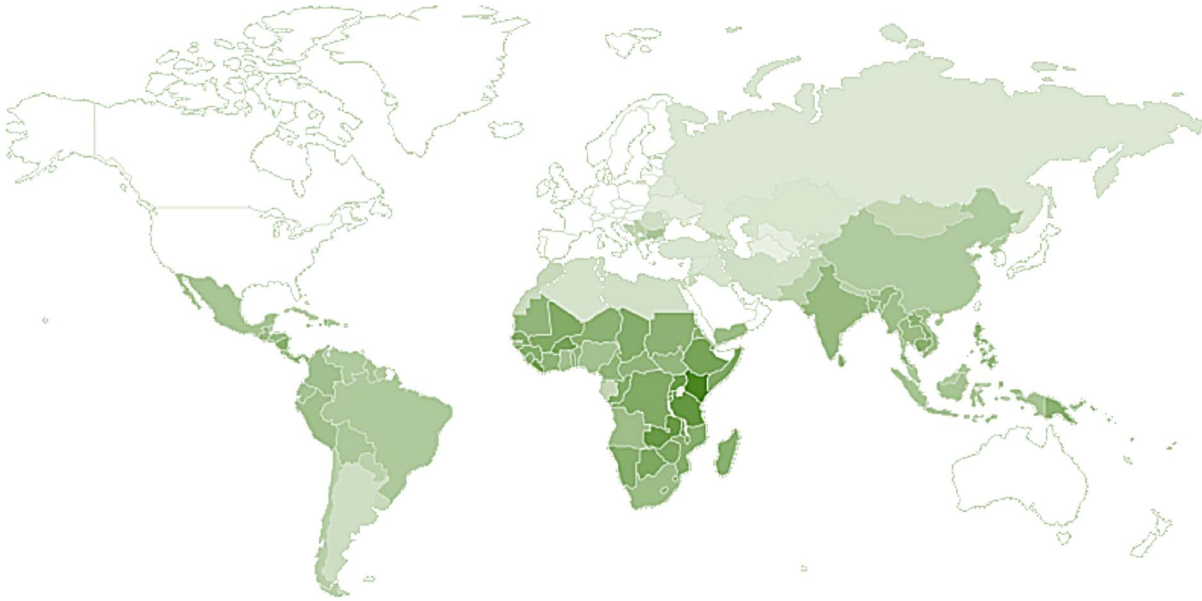

Fig. 5. Chloropleth plots showing viability scores for PV-eCook (top). Green indicates most viable, red least viable. Note: High Income Countries (HICs) were not included in the analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

using regional means, however this was particularly challenging for politically isolated countries, fragile states and SIDS,[13] all of which had many missing data points and a tendency for any available data to be out of date. Also, the national scale MCDA process did not allow for subnational resolution; which is particularly important for larger nations such as China and India.

Reducing this vast amount of data into one number blurs together many of the interesting market dynamics that govern what role eCook is most likely to play in that context. The MCDA techniques employed offer a methodology to compare unique country contexts, however it is purely quantitative and needs to be contextualised by qualitative data to fully understand the significance of the results. No MCDA can offer a plug and play methodology – the value comes out of the weighting process, as much as the weighting results. It does not necessarily generate *the* right answer, but gives an answer relevant to the key questions. As a result, a qualitative analysis of the 3 SSA countries with highest PV-eCook viability scores were shortlisted to contextualise the statistics and highlight the unique opportunities for eCook in each country.

The majority of the factors included in this analysis are static factors, which do not reflect the momentum for change within each particular country. This could be incorporated into future iterations of the eCook GMA by calculating the % change in each factor during the last 3 years and turning each indicator into a compound indicator that would consist of both the absolute value and the rate of change.

5. Results

5.1. Basic viability scores point to Africa

The weighting and ranking process was designed to predict the ease of rolling out the eCook concept in each particular country context. Fig. 5 presents the results for PV-eCook (see Appendix C for Grid-eCook) as global choropleth plots, whilst Fig. 6 focuses in on the results for PV-eCook in Africa, breaking the key factors down into a histogram.

Figs. 5 and 6 show that PV-eCook is clearly most viable in Africa, particularly in East and Southern Africa. Perhaps unsurprisingly, Kenya is both the easiest market to enter and, as will be seen below, has one of the biggest target market segments. It is closely followed by several East and Southern African nations, most notably Tanzania, Zambia and Uganda.

Closer inspection of Fig. 6 shows that the solar resource, grid access and polluting fuel users seem to have the largest influence on the outcome of the ranking. Saharan nations score far above their Southern African counterparts for solar resource. Low levels of access to the national grid in countries such as Angola, Chad and Sierra Leone push them up in the rankings above more developed nations such as South Africa and Ghana, where a much smaller fraction of the population is off-grid. Liberia, Guinea-Bissau, Madagascar and Rwanda all receive maximum points for polluting fuel users, as 100% of their population reportedly cook using firewood, charcoal, crop waste or kerosene. Gabon and South Africa sit at the other end of the scale with much of their populations cooking on LPG and electricity respectively.

To explore the underlying reasons behind these outcomes, the following sub-sections present further explorations of the data to complement the viability scores obtained from the MCDA. Firstly, they compare the viability scores with the absolute sizes of the key PV-eCook target market segments. Secondly, they compare the predicted future costs of cooking on a PV-eCook to the relative fuel prices found in each country to determine where the price tipping points are likely to occur first. Finally, the statistics are contextualised by a qualitative description of the potential markets that exist in three countries with highest potential, Kenya, Tanzania and Zambia.

5.2. Size of the market

While the viability scores show that conditions are favourable for transitioning from polluting fuels to PV-eCook, they do not indicate the size of the potential market. To normalize comparisons, the viability score includes indicators on the percentage of the population that are off-grid and/or using polluting fuels, but not the absolute population numbers. Whilst transitions may occur relatively quickly in high viability markets, they may only affect a small number of HHs.

Fig. 7 compares the two overlapping key market segments targeted by PV-eCook: rural-off grid population (y-axis) and commercialised polluting fuel users (x-axis). These two market segments clearly overlap, however the degree to which this occurs is uncertain as many rural off-grid HHs will be able to access fuel for free (or at least only at the cost of their own time) and many commercialised polluting fuel

[13] Smaller Island Developing States.

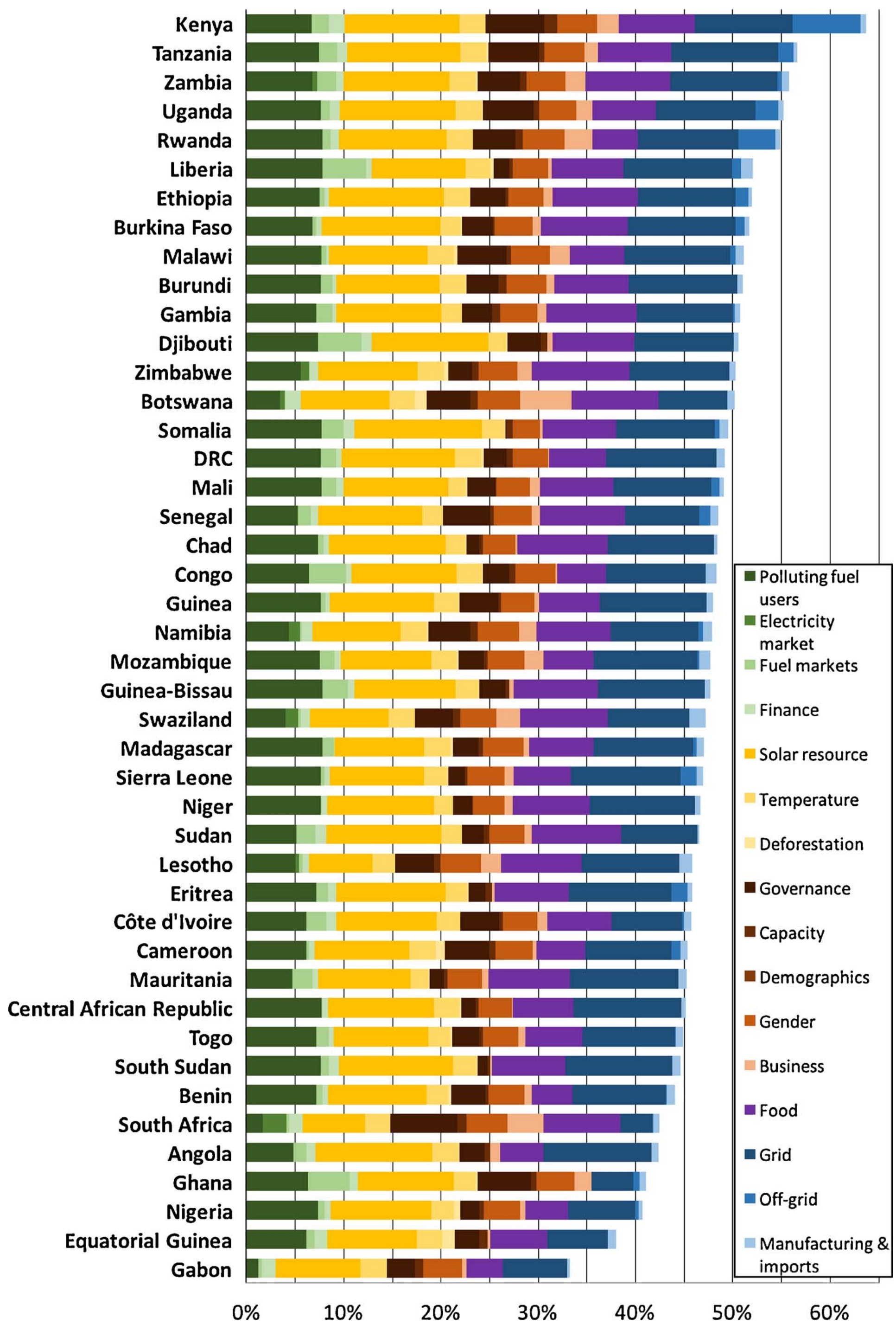

Fig. 6. PV-eCook score breakdowns by category and factor.

users will reside in urban areas. However, the higher the number of people in each segment, the more people are likely to fall in this overlapping region. The colour of the two letter labels represents that country's viability score, meaning that the ideal context would appear in dark green positioned towards the top right of Fig. 7, indicating large rural off-grid populations, with many commercialised polluting fuel users.

Kenya, Tanzania and Uganda all represent large markets that are likely to transition quickly (dark green colour indicates high viability score). Nigeria represents the largest market, however its viability score is one of the lowest (indicated by orange colour), indicating that although a transition to PV-eCook could have a big impact, it is not likely to occur very quickly. Ethiopia has a large rural population, however the fact that it sits to the left of the origin to top right diagonal indicates that it is likely that a smaller proportion of these people purchase their fuel. Zambia, Rwanda, Malawi and Somalia also represent significant populations that fit into our target market segments and would be relatively easy to reach (i.e. high viability scores).

The use of grid electricity for cooking barely happens in Sub Saharan Africa, with the notable exceptions of South Africa, Ethiopia, Namibia, Zambia and Zimbabwe. This is thought to be principally due to inaccessible, unreliable and/or expensive electricity (or at least the perception that it is expensive). However, the presence of electric cooking in these exceptions does suggest that there are few significant cultural

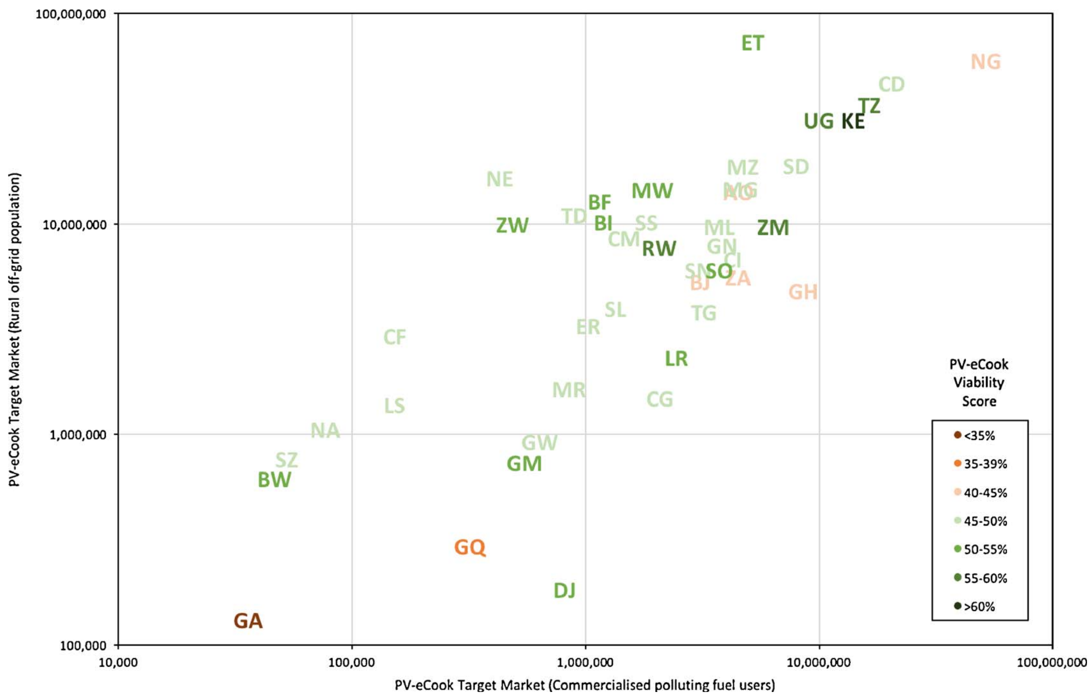

Fig. 7. Target market segments for PV-eCook in Sub-Saharan Africa.

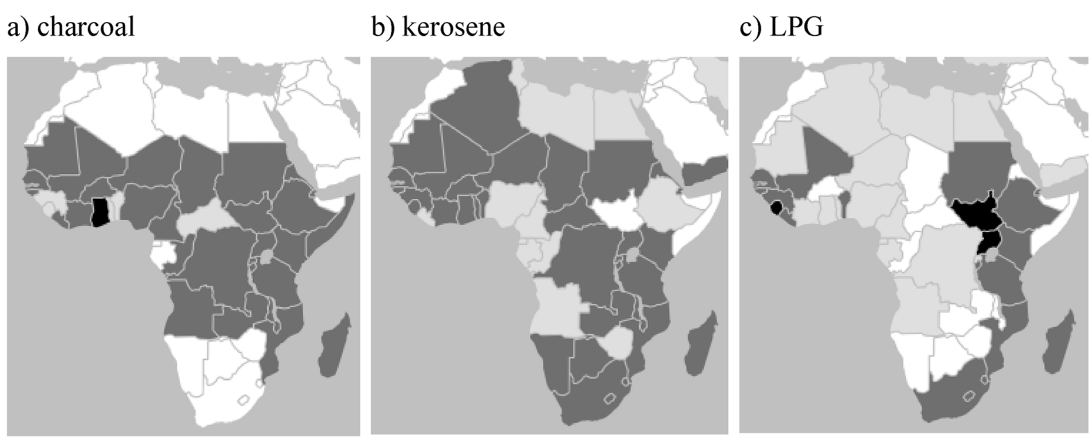

Fig. 8. Chloropleth visualisation of price parity analysis for PV-eCook vs. a) charcoal—29.9 MJ/kg, open fire, 20% efficiency, retail price of a sack of charcoal plus 40% poverty premium to account for HHs purchasing in small quantities, b) kerosene—34.9 MJ/l, 55% efficient stove, 30% poverty premium to account for HHs purchasing in small quantities. and c) LPG—44.8 MJ/kg, 60% efficient stove, no poverty premium.. Black = cheaper to cook with PV-eCook in 2020 under all of Leach & Oduro's [16] scenarios. Dark grey = cheaper to cook with PV-eCook in 2020 some of Leach & Oduro's [16] scenarios. Light grey = not yet cheaper to cook with PV-eCook in 2020 under any of Leach & Oduro's [16] scenarios. White = no data available.

barriers to cooking with electricity in these countries and that cooking with electricity is more likely to be an aspiration for rural off-grid HHs. With high levels of access, high reliability and low unit cost, South Africa leads the way for electric cooking uptake in Sub-Saharan Africa [34–36].

5.3. Fuel parity

One of the most critical factors in assessing the market for PV-eCook is the attractiveness of the existing commercialised polluting fuel market segments. 'Fuel Attractiveness' in the viability analysis is the normalised product of the price and the percentage of current users. Three additional price parity analyses were carried out to illustrate which countries offer the greatest economic opportunities for PV-eCook in 2020 in existing charcoal, kerosene or LPG markets.

Using Leach & Oduro [16] and Scott et al.'s [37] processes for comparing energy delivered to the pot, it was found that for countries with charcoal prices below 0.31USD/kg (assuming 30% efficient ICS), kerosene prices below 1.00USD/l or LPG prices below 1.39USD/kg, it will be cheaper to use these fuels than PV-eCook in 2020 under all scenarios.[14] In countries with charcoal prices above 1.35USD/kg, kerosene prices below 4.34USD/l or LPG prices below 6.07USD/kg, in 2020 it will be cheaper to use PV-eCook than these fuels under all scenarios. Countries in between these ranges will be cheaper under some scenarios and more expensive under others, suggesting that some markets are likely to emerge within each country.

Fig. 8 shows that Africa's charcoal markets offer a huge opportunity for PV-eCook. By 2020, it is predicted that it could be cheaper for some HHs in almost all (31/36) of the SSA countries included in the analysis to transition to PV-eCook. In fact, charcoal prices in Ghana are reportedly so high that it is predicted that PV-eCook will be more cost

[14] A 40% poverty premium was added to all fuel costs to represent the increased costs to poorer HHs who are only able to purchase in small quantities, however it should be noted that the price in rural charcoal producing areas will be lower.

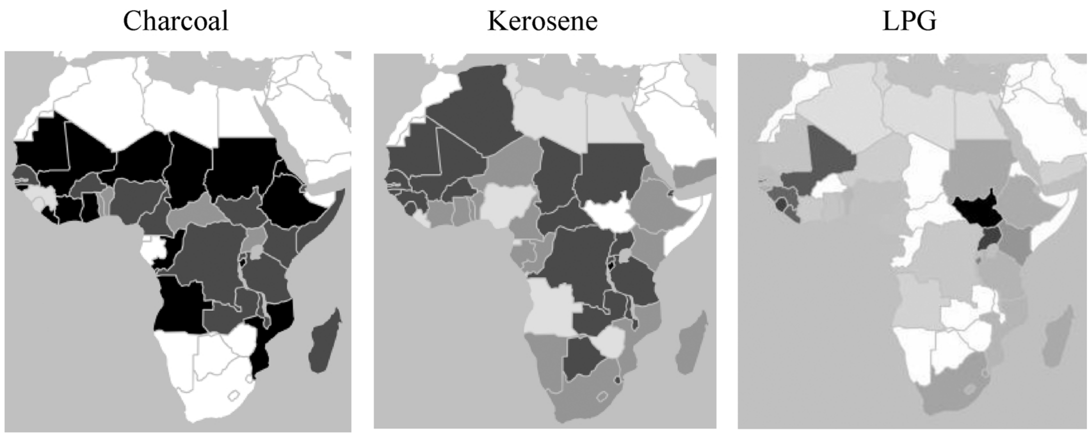

Fig. 9. Chloropleth visualisation of price parity analysis for eCook vs. a) charcoal, b) kerosene and c) LPG. Black = cost effective to switch if eCook falls to below 0.3USD/kWh. Dark grey = cost effective to switch if eCook falls to 0.2USD/kWh. Grey = cost effective to switch if eCook falls to 0.1USD/kWh. Light grey = eCook must fall below 0.1USD/kWh before it is cost effective to switch. White = no data available.

effective under all scenarios. What is more, rapid deforestation is pushing up the price of charcoal in many SSA countries [27], meaning that the opportunity is likely to be even greater than indicated, as these charcoal prices were obtained from a 2017 survey.

In three quarters (33/42) of SSA nations, PV-eCook is predicted to be cost-effective against kerosene under some scenarios. It should be noted that the 9 countries where it is not predicted to be cost-effective under any scenarios include the region's major oil producing nations such as Angola, Nigeria and Cameroon. PV-eCook could become economically viable in these countries if policy makers could be persuaded to divert state subsidies for kerosene into PV-eCook, simultaneously freeing up more oil to generate more revenue through sales to overseas markets and building a national renewable energy economy. The outlook for LPG is complex. High LPG prices in some West and East African nations appear to create an opportunity in 2020, however the timing of this opportunity is likely to be different than Fig. 8 suggests.[15]

As discussed above, Kittner et al. [22] suggests that the main eCook component cost, battery storage, is following Leach and Oduros' optimistic scenario, with faster than expected learning curves suggesting 200USD/kWh could be a reality by 2019. Similarly, as mentioned previously, initial prototyping has shown that efficiency gains in the cooking processes can even exceed Leach and Oduro's optimistic scenario for energy demand. We therefore finish this section with an alternative set of choropleths for Africa, in the hope they become a decision tool for policy actors. Fig. 9 illustrates the LCoE[16] thresholds eCook will have to cross to be at price parity with the alternative fuels.

5.4. Case studies

While this national level comparative analysis gives some indication of where eCook is likely to take hold first and/or have the greatest impact, there is a need to nuance the findings for each country. This section presents an initial exploration of the potential markets in Kenya, Zambia and Tanzania. At the time of writing, the researchers are carrying out field research in all three countries to collect even more granular data.

[15] The LPG prices obtained for this analysis range from 2012 to 2017, yet globally, LPG has been steadily decreasing in price since 2010. What is more, LPG is an emerging technology in many countries and as markets develop, economies of scale inevitably bring the price down. As a result, the current LPG price in many countries will be lower than predicted here and is likely to keep dropping until 2020 when the production surplus from the exploitation of shale gas begins to even out with the increasing demand for what is currently relatively cheap LPG [23]. However, shows that by 2026, global LPG prices are expected to return to 2010 levels, suggesting that a window of opportunity will open up for PV-eCook as the next decade unfolds.

[16] Levelised Cost of Energy.

5.4.1. Zambia

Zambia ranks highly on the viability scores, market size and the price parity analysis and is of particular interest because in 2013, 12% of Zambians (2 million) were already using electricity as their primary fuel [38]. This suggests that electrical cooking appliances and Zambian cuisine are compatible and that electric cooking is likely to be an aspiration of those currently without access to the national grid. However, recent load-shedding caused many of these users to revert back to charcoal [39]. Charcoal production increased to meet this growing demand, accelerating deforestation and stepping up the pressure on Zambia's already strained natural resources [39]. Neither LPG nor kerosene markets have yet emerged in Zambia.[17]

Zambia scores highly for PV-eCook viability, as 59% of Zambians (10 million) live in rural areas, 96% of whom are off-grid [40] and the market for pico-solar products and SHS is expanding rapidly [41] report 15,000 sales in Zambia in the second half of 2016. Zambia also has very favourable environmental conditions.[18]

37% of Zambians (6 million) use charcoal as their primary cooking fuel – only Liberia, Haiti and Togo have higher market shares [38]. 24 responses were received from Zambia for the survey of GACC experts, indicating that prices are at moderate levels (0.18USD/kg in rural charcoal producing regions, rising to 0.27USD/kg in urban areas and reaching a maximum of 0.38USD/kg). The price parity analysis showed that irrespective of whether a HH uses charcoal on an open fire, in an ICS or even in an advanced ICS, it is still cheaper to cook with grid electricity.

Analysis of the FAO's food consumption database suggests that Zambian cuisine requires relatively low energy input in the cooking process (2.61 kWh/HH/day). The database suggests a predominantly vegetable-based diet, with maize, cassava, sweet potatoes and other roots & tubers creating the highest energy demand. Zambia's main staple, nshima, is a maize- or cassava-based dish similar to Kenya/Tanzania's ugali. It requires significant stirring throughout the cooking process, reducing the potential energy savings from insulated pots and even lids, however it can be carried out satisfactorily on a relatively low power hob.

5.4.2. Kenya

Kenya has the highest PV-eCook viability score in the world. 72% of Kenyans (35 million) live in rural areas, 87% of whom (31 million) do not have grid access [40]. Kenya is East Africa's commercial hub and

[17] Presumably due to the long overland supply chain that would need to be established to import these fuels into this landlocked Southern African nation.

[18] WorldClim [44] reports monthly average solar irradiation: 4.4–5.8 kWh/m^2/day and temperatures: 17–25 °C.

has a strong track record for innovation in the energy for development space. M-Pesa was the first mobile money system to reach scale anywhere in the world, which in turn enabled innovative energy service companies, such as M-Kopa, to roll out pay-as-you solar solutions for the mass market. In the second half of 2016, 670,000 pico-solar products and SHS were sold in Kenya, making it the second biggest market place in the world (surpassed only by India, which has 27 times greater population) [41]. Leveraging Kenya's extensive network of entrepreneurs and established institutions who are already actively rolling out energy access solutions could allow eCook to evolve at a much faster rate than most other contexts.

Deforestation is a major issue in Kenya, with an estimated 64% of the biomass harvested each year for HH fuel classified as non-renewable [42]. 86% of the population (41 million) cook on polluting fuels, with 12% (6 million) cooking primarily with kerosene and 17% (8 million) on charcoal [38]. The price of charcoal in major cities has been steadily increasing in recent years as nearby forests are exhausted, increasing the distance and therefore the cost of transporting charcoal from production areas to urban centres [27]. 21 responses were received from the GACC experts survey, which estimated low prices in rural charcoal producing regions (0.16USD/kg), staying relatively low in urban areas (0.28USD/kg) and only increasing to a moderate level in Nairobi (0.44USD/kg). It is clear that the value of charcoal does not yet accurately reflect the damage caused by unsustainable biomass harvesting in Kenya, as the availability of relatively cheap charcoal means that it is still attractive as a HH fuel.

Kenya has been a hotbed for ICS programmes with a significant amount of time and money already invested in social marketing programmes. For example, GACC [43] has recently launched the Shamba Chef TV series, which is designed to show people how to cook nutritiously and save both energy and money with cleaner cooking appliances. Leveraging the combined effects of both of these social marketing campaigns on the benefits of clean cooking and the business models and customer relationships established by Kenya's myriad pay-as-you solar companies will no doubt greatly accelerate the uptake of PV-eCook. Organisations wishing to specifically promote PV-eCook could build upon this foundation by developing similar social marketing programmes on cooking with electrical appliances targeted at existing SHS users.

Interestingly, LPG is still relatively expensive in Kenya (2.23USD/kg), putting the 5 million Kenyans (11%) [38] who use it as their primary fuel well above the parity line. However, as the LPG market continues to grow, these prices are likely to continue to fall as supply chains become more established. What is more, oil production is just beginning in the North, which is likely to lock Kenya into this pathway until these domestic reserves dwindle.

Whilst the statistics show that Kenya has an almost ideal climate, in reality there are a diverse range of climates within this large country.[19] Kenya also has a more diverse range of cuisines than Zambia. However, at 3.16 kWh/HH/day, the energy requirement as predicted by the analysis of the FAO food consumption database is still fairly low. The database suggests a more balanced diet, with maize, potatoes, wheat, cassava, sweet potatoes and beans all major contributors to the energy requirement for HH cooking. The main staple, ugali, is almost identical to Zambia's nshima.

[19] For example, the monthly average temperatures for the country as a whole range from 23 to 26 °C [44], yet the arid plains of Turkana are extremely hot, whilst Nairobi is much higher, so it stays cooler. As a result, batteries should be expected to have shorter lifetimes in Turkana, whilst fuel stacking due to the dual use of stoves for space heating and cooking is likely to be higher in Nairobi. As a national average, the solar resource maintains a minimum monthly average of 4.7 kWh/m^2/day throughout the year, with an additional 1 kWh/m^2/day available in the sunniest month [44]. However, equally large variations in the solar resource should be expected across the country.

5.4.3. Tanzania

Like neighbouring Kenya and Zambia, Tanzania has enormous potential for PV-eCook. 68% of Tanzanians (38 million) live in rural areas, 96% of whom (37 million) are not connected to the grid [40]. The Tanzanian off-grid industry is growing rapidly in order to meet the needs of this huge market segment, with 185,000 SHS and pico-solar products sold in the second half of 2016 [41]. What is more, the climatic conditions are very favourable, offering a strong and stable solar resource (monthly averages ranging from 4.5 to 5.4 kWh/m^2/day) and comfortable temperature range (monthly averages ranging from 20 to 24 °C) [44]. However, it should be noted that like Kenya, there is significant regional variation in climatic conditions across this even larger country.

15 million Tanzanians (27%) use charcoal as their primary HH cooking fuel – making it the fourth largest domestic charcoal market in the world after DRC, Myanmar and the Philippines [38]. 5 experts from the GACC database responded to the charcoal price survey, indicating that prices in Tanzania are currently only at moderate levels (0.45USD/kg in major cities). However, although Drigo et al. [42] estimate that only 15% of biomass harvested for HH wood fuel in Tanzania is non-renewable, this nationally averaged figure masks some important trends. 70% of the charcoal produced in Tanzania is transported to Dar es Salaam, creating a hotspot of rapid tree felling in the surrounding area. Prof. Jumanne Maghembe, Natural Resources and Tourism Minister, estimates that less than 30% of this is actually consumed in the city, with the remainder *"exported to Asia through Zanzibar and porous Indian Ocean illegal ports"* [45].

As a result, earlier this year, the Government of Tanzania banned both the export of charcoal and its transportation between districts [46], with the intention that charcoal consumers will transition to cleaner fuels, specifically LPG. However, Tanzania has a long history of banning charcoal, often with unintended consequences. Havnevik [47] describes the impact of the charcoal ban in 1979, which had little effect on deforestation, as the same quantity of charcoal was produced and either sold at much higher prices on the black market or stored until the ban was lifted a month later. There has been considerable public opposition to the imposition of another outright ban, pointing out that alternatives that are "*accessible, available and affordable all the time*" need to be in place first [46]. As a result, a gradual tightening of restrictions in order to reduce the availability of charcoal, push up the price and invoke a gradual transition, seems most likely [48]. This presents a considerable opportunity for eCook, as although LPG is being targeted as the primary fuel to enable a transition away from charcoal, there is considerable interest in electricity, with access to the national grid likely to be the major barrier.

Tanzanian food is predicted to require slightly higher energy for HH cooking (3.65 kWh/HH/day). The FAO food consumption database suggests cassava, sweet potatoes and maize are likely to be the major energy consumers. Ugali is again the main staple, however, like Kenya, this physically and culturally diverse country has a broad range of regional cuisines that are likely to have significantly different energy requirements.

6. Conclusions and further work

The call for a transformative approach to the twin challenges of clean cooking and electrification, something other than 'business as usual', could be addressed by eCook. A growing body of work has confirmed that in the next 5 years the cost of cooking with such a system will be of the same order as cooking with conventional fuels. These statements have been made on an 'energy in the pot' comparison with other commercialised polluting fuels and LPG and therefore do not apply to polluting fuels that are not traded (i.e. collecting wood or dung from farmland or forest).

This paper has sought to identify which African countries present the biggest opportunity for eCook. Viability depends on many factors ranging from existing infrastructure to human capacity to fuel costs. MCDA techniques were employed to indicate the relative viability of countries in the world. It was found that the East and Southern Africa offer the most favourable conditions for rapid uptake of PV-eCook anywhere in the world, most notably:

- a strong and stable solar resource;
- hot climates that limit stove use for heating;
- stable governments with enabling energy policy;
- relatively empowered women;
- favourable business cultures;
- staple foods that are compatible with battery-supported cooking appliances;
- significant numbers of people already cooking with electricity (Southern Africa only); and
- strong markets for SHS paving the way.

East and Southern Africa also contain significant sizeable markets and within the next five years the anticipated costs of eCook are likely to be comparable to the commercialised polluting fuels that are currently used by millions of people, many of whom are off-grid.

The paper draws attention to three countries (Zambia, Kenya and Tanzania) with highest viability, sizeable markets and favourable fuel price parity, presenting a brief overview of each market. These countries will likely transition first according to the data – however we note that other countries are close on the viability scores and much will depend on the agencies engaging with this potential transformation.

6.1. Further work

There is a remarkable lack of data on cooking processes under the more controllable conditions made possible by modern fuels. Cowan [36] provides one of the few existing studies, monitoring real household cooking for LPG, electricity, kerosene and ethanol stoves. The Low Cost Technologies project[20] is currently undertaking 'cooking diary' studies to characterise the way people cook on electricity in Kenya. However, we use this paper to call for more studies on how people cook when using modern fuels like LPG and electricity.

At the time of writing, detailed in country research is already underway to explore the markets for eCook in Zambia and Tanzania. This study enabled the research team to determine which countries to focus on, however as a desk-based study, many assumptions were made due to the limited data available. In particular, this in country work aims to gain much greater insight into culturally distinct cooking practices and explore how compatible they are with battery-supported electric cooking. To achieve this, the programme of research includes the following key methodologies:

- Cooking diaries – asking households to record exactly what they cook, when and how for 6 weeks.[21]
- Choice modelling surveys – asking potential future eCook users which design features they would value most in a future eCook device.
- Focus groups – offering a deeper qualitative exploration of how people currently cook, how they would like to cook in the future and the compatibility of these cooking practices with the strengths and weaknesses of cooking on battery-supported electrical appliances.
- Techno-economic modelling – refining Leach & Oduro's [16] model and adapting it to reflect the unique market conditions in each national context.
- Protoyping – using the data from the above methodologies to shape the next generation of eCook prototypes in a participatory design process involving local entrepreneurs and future end users of eCook devices.
- Stakeholder engagement – bringing together key policy, private sector, NGO, research and community actors to explore the opportunities and challenges that await eCook in each unique national context.

This is being undertaken by a core research consortium of Gamos, Loughborough University and the University of Surrey through partnerships established with experienced local research institutions in each country. The consortium has already established links with similar institutions in other countries and welcomes the participation of further actors who also see the potential for eCook, particularly those based in countries identified by this study as having high viability and large target markets. The activities of the research consortium are collated on the online portal PV-eCook.org.

Appendix A. New datasets assembled for the GMA

The energy requirement for cooking varies greatly between cultures, depending upon both the foods to be cooked and the culturally embedded preparation techniques. However, published data on energy use for cooking with electricity are scarce. The UN FAO's[22] database of national food consumption breaks down the food eaten in each country into categories, listing the total number of kilograms of each eaten per capita per year. A structured analysis was carried out of the energy requirement of the typical preparation methods for each type of food. The analysis revolved around breaking down all cooking operations into three categories:

1. high power, modelled at 1000 W, e.g. bringing water to the boil;
2. medium power, modelled at 750 W, e.g. shallow frying chapatis; and
3. low power, modelled at 500 W, e.g. simmering tougher cuts of meat.

The amount of time required to boil, fry, simmer (or equivalent) a standard portion of each food was estimated using typical preparation methods. For foods with many preparation methods (e.g. maize can be boiled as sweetcorn, fried as corn tortillas or simmered and stirred as ugali), the main techniques were modelled and an average taken. The total annual consumption per capita was then divided by the standard portion size to estimate how much energy the average person in that country would use to cook that category of food each year. Summing for all the food categories gives an estimate for the total HH energy consumption per person per year for that particular nation.

The solar resource and temperature are both critical design parameters for PV-eCook. WorldClim [44] global GIS (Geographic Information System) layers representing mean monthly solar irradiance and mean monthly temperature were processed to extract nationwide averages for each country. The minimum monthly means and standard deviation between monthly means were both used to prioritise countries with a high and steady

[20] Led by University of Sussex and funded by EPSRC and DFID.

[21] Firstly, using their traditional fuels and appliances and simply recording data on energy use and cooking practices. Then transitioning to electricity and recording identical data that will enable much more detailed characterisation of the 'cooking load' on battery systems and the compatibility of a range of electrical appliances with specific cooking practices.

[22] United Nations Forestry and Agriculture Organisation.

solar resource. For temperature, the number of degree days below 20 °C were calculated from the monthly average temperature data as an indicator for the likelihood of stoves serving the dual purpose of stove heaters. Degree days above 25 °C using the same monthly mean temperature dataset was also used as an indicator for accelerated battery degradation.

Of the 'commercialised polluting fuels', the retail prices of charcoal proved to be the most challenging datasets to obtain. The centralized supply chain through which kerosene, electricity and LPG are produced and distributed meant that retail prices could be assembled relatively easily from pre-existing datasets, national regulatory authorities or press searches. However, in most countries, charcoal is an informal commodity, with decentralised production and an unregulated supply chain. As a result, there is no 'standard price' for charcoal in such markets. The price varies with a huge range of factors, including the quantity purchased, the quality of tree/coconut/etc. used in production, the distance from charcoal producing areas, rainy/dry season, permits and/or bribes for production, transportation and/or retail, etc.

The charcoal price dataset was assembled by surveying members of the GACC[23] Partners Database, triangulated with data from the literature and press searches where available. To produce comparable results, the analysis focussed on the retail price of a standard sack of charcoal. Sack weights varied from 10 to 90 kg and respondents were asked to clarify if the stated weight was the weight of charcoal in the sack or if the sack was repurposed (e.g. maize flour sack), then the approximate weight of charcoal it would be likely to contain. Responses were grouped into rural charcoal producing regions (or lowest price), urban areas (or average price) and capital city (or maximum price).[24] 428 experts from across the 55 countries with over 2% of the population using charcoal as their primary cooking fuel were contacted by email or telephone. A total of 149 responses were received, implying a high response rate of 34%. For countries without any survey responses, the UN FAO import/export price for charcoal was used as a guide for interpolation, as data was available across all 55 countries. However, only a weak correlation between the import/export price of charcoal and the survey responses was found, indicating that although clearly connected, the two markets have different dynamics. In the absence of any other datasets, this was deemed to be the only possible method of filling in the missing datapoints as no regional correlation was observed.

Appendix B. Categories, sub-categories, indicators and data sources used in the eCook GMA. Note: some factors only apply to Grid-eCook, so received zero weighting for PV-eCook

	Factor	Indicator	Cumulative Weight	Units	Data Source
Economics	Polluting fuels	Users	8%	%	WHO [38] HH Energy Database
	Electricity market	Users (for cooking)	2%	%	WHO [38] HH Energy Database
		Standard tariff	0%	$/kWh	IEA [49] Africa Energy Outlook, RISE Country Profiles [50], World Bank [51] Ease of Doing Business Country Profiles, Tao & Finenko [52]
		Lifeline tariffs	0%	Lifeline tariff attractiveness factor ($/kWh * kWh allowance)	RISE Country Profiles [50], national regulatory authorities
	Fuel markets	LPG	1%	Attractiveness factor (% users * price)	WHO [38] HH Energy Database, IMF Fuel Price Dataset [53], Pacific Community [54] Fuel Price Monitor, GlobalPetrolPrices.com [55], EU & AfDB [56], national regulatory authorities
		Kerosene	4%	Attractiveness factor (% users * price)	WHO [38] HH Energy Database, IEA [49] Africa Energy Outlook, Lighting Africa [57], Pacific Community [54] Fuel Price Monitor, IMF Fuel Price Database [53], national regulatory authorities
		Charcoal	4%	Attractiveness factor (% users * price)	WHO [38] HH Energy Database, phone & email survey of GACC [43,58] Partner Directory members, detailed literature review & press searches for 4 focus countries, UN FAOSTAT [59,60] charcoal import/export dataset
	Finance	GNI per capita	2%	USD	World Bank [40] World Development Indicators
		Lending interest rate	0%	%	World Bank [40] World Development Indicators
		Mobile money	1%	Subscribers	World Bank [40] World Development Indicators
		R&D expenditure	0%	(% of GDP)	World Bank [40] World Development Indicators
		Net bilateral aid flows from DAC donors	1%	(current US$ per capita)	World Bank [40] World Development Indicators

[23] Global Alliance for Clean Cookstoves.

[24] Small quantities in the capital city were also included in the survey as this was expected to be the highest price that the urban poor would be paying, however the results were excluded, as even small errors in the weight introduce large variations in the $/kg.

Physical	Solar resource	Magnitude (minimum monthly average)	6%	$kWh/m^2/yr$	WorldClim [44] Global Climate Data GIS
		Seasonal variation (S.D.)	7%	$kJ/m^2/yr$	WorldClim [44] Global Climate Data GIS
	Temperature	Cold	2%	Degree days (below base 20)	WorldClim [44] Global Climate Data GIS
		Hot	1%	Degree days (above base 25)	WorldClim [44] Global Climate Data GIS
	Deforestation	fNRB[25]	1%	%	Drigo et al. [42] Pan-tropical analysis of woodfuel supply, demand and sustainability
Human	Governance	Control of Corruption	0%		World Bank [61] World Governance Indicators
		Government Effectiveness	1%		World Bank [61] World Governance Indicators
		Political Stability and Absence of Violence/ Terrorism	0%		World Bank [61] World Governance Indicators
		Rule of Law	1%		World Bank [61] World Governance Indicators
		Renewable energy policy	7%	%	ESMAP [50] Regulatory Indicators for Sustainable Energy
	Capacity	Technicians in R&D (/million ppl)	1%		World Bank [40] World Development Indicators
		Researchers in R&D (/million ppl)	1%		World Bank [40] World Development Indicators
		Literacy rate, adult female	1%	% of females ages 15 and above	World Bank [40] World Development Indicators
	Demographics	Population growth	0%		World Bank [40] World Development Indicators
		Rural population	0%	(% of total population)	World Bank [40] World Development Indicators
		Rural population growth	0%	(annual %)	World Bank [40] World Development Indicators
		Urban population	0%	(% of total population)	World Bank [40] World Development Indicators
		Urban population growth	0%	(annual%)	World Bank [40] World Development Indicators
		Population living in slums	0%	% of urban population	World Bank [40] World Development Indicators
	Gender	Gender Development Index	5%	(% of HHs)	UNDP [62] Gender Development Index
	Business	New business density	3%	(new registrations per 1000 people ages 15–64)	World Bank [40] World Development Indicators
		Ease of doing business index	3%		World Bank [40] World Development Indicators
Food	National diet	Energy in HH cooking	10%	kWh/HH/day	[59] Food Balance Sheets

Infrastructure	Grid	Total access	0%	%	World Bank [40] World Development Indicators
		Rural access	11%	%	World Bank [40] World Development Indicators
		Urban access	0%	%	World Bank [40] World Development Indicators
		Renewable electricity output	0%	(% of total electricity output)	World Bank [40] World Development Indicators
		Time required to get electricity	0%	(days)	World Bank [40] World Development Indicators
		Load shedding	0%	blackouts/month	World Bank [51,40] Enterprise Surveys & Doing Business Project
		Electric power transmission and distribution losses	0%	(% of output)	World Bank [40] World Development Indicators
	Off-grid	SHS	11%	Sales per 1000 people	GOGLA et al. [41] Global Off-Grid Solar Market Report Semi-Annual Sales and Impact Data
	Manufacturing & imports	Imports of goods and services	1%	(% of GDP)	World Bank [40] World Development Indicators
		Manufacturing, value added	1%	(% of GDP)	World Bank [40] World Development Indicators

Appendix C. Comparative MCDA weighting and results for Grid eCook

To reflect the unique characteristics and target markets of Grid-eCook and PV-eCook, two separate weighting sets were produced (see Fig. 10). For example, Grid-eCook weightings were designed to prioritise high levels of access to **unreliable** grid infrastructure, but with low unit costs of electricity. In contrast, PV-eCook weightings emphasised high and consistent solar resource, large rural off-grid populations and a strong SHS industry paving the way. Both sets of weightings prioritise countries with favourable energy policy, business ecosystems, strong governance, capacity and finance. Deforestation, gender equality and the HH energy requirements of typical diets are also considered equally important for both PV-eCook and Grid-eCook. High numbers of polluting fuel and electric stove users are seen as positive for both, as are attractive fuel markets, however LPG is seen as more of an urban fuel, so has less influence on the viability of PV-eCook.

Fig. 10. Cumulative weightings for each factor under the PV-eCook (left) and Grid-eCook (right) weighting sets.

The results of this alternative weighting set can be seen in Fig. 11, which shows that Southern Africa, Latin America and South Asia offer the most favourable contexts for Grid-eCook. Grid-eCook's suitability in Africa is still of relevance though, as sales into urban centres to strengthen an unreliable grid could provide an early entry market from which the supply chains and awareness for eCook could be established, offering PV-eCook a springboard to reach out into more inaccessible off grid areas.

[25] Fraction of Non-Renewable Biomasss.

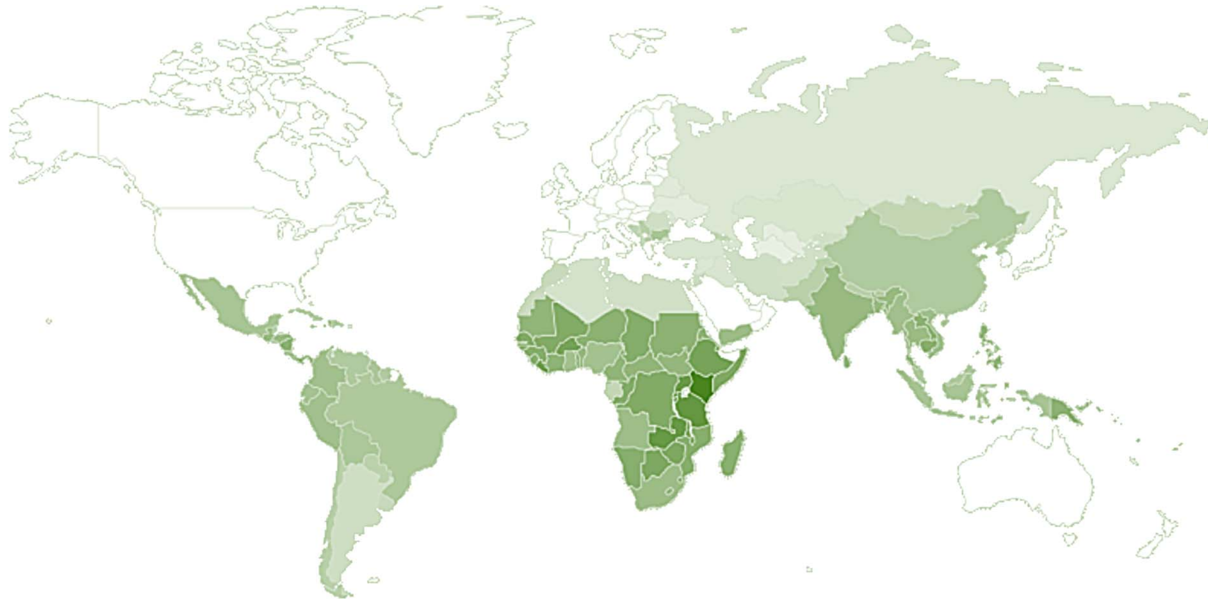

Fig. 11. Chloropleth plot showing viability scores for Grid-eCook. Green indicates most viable, red least viable. Note: High Income Countries (HICs) were not included in the analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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