Modelling the costs and benefits of moving to Modern Energy Cooking Services – methods & application to three case studies

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Executive Summary

Globally, 2.8 billion people still cook with biomass, resulting in interlinked health, environmental and social challenges. Indeed, in ESMAP (2020b), the number of people who do not have access to modern energy cooking (mecs) is calculated at 4 billion. Yet access to electricity has made significant gains over the last 10 years. The number of people without electricity has fallen 770 million in 2019 (IEA, no date). Many of those gains can be found in developing Asia, and are in part due to the increasing urbanisation of the world. At this headline level, we can see that of the 2.8 billion relying on biomass for cooking (or the 4 billion without access to mecs), 2 to 3 billion people have some form of access to electricity but still cook with polluting fuels.

Alongside the Sustainable Development Goals, the world is increasingly aware of its need to mitigate Climate Change. The coming decade will see a significant push towards net zero carbon as countries set targets for 2030, 2040 and 2050. Part of this will be pivoting existing electrical infrastructure from fossil fuels to renewables, building on the cost effectiveness of large scale renewable energy and the opportunities for decentralisation of power generation. As grids become cleaner, the opportunity to utilise the infrastructure to provide 'sustainable' modern energy for cooking will be increased further particularly in Asia.

Many of those without access to electricity are found in Sub Saharan Africa. Current scenarios envisage more than 50% of the energy access gains being made through stand-alone systems and mini-grids, rather than grid connection.

Electric cooking is one of the key options for a transition to modern energy cooking services, and SDG7 aims for universal access to electricity by 2030. The promotion and scaling of electric cooking faces a number of barriers, including perceptions that it is generally too expensive, and that it is not feasible with anything other than a strong grid connection. These perceptions are outdated, and recent research and ongoing trials have demonstrated that electric cooking is attractive to many users and that it can be cost-competitive for households in all types of electricity access context (ESMAP, 2020a).

In this paper the authors have come together to present modelling of different aspects of the cooking transition. The toolkit of models and analysis represents the range of benefits and impacts of different approaches to delivering clean cooking services, across full supply chains and all life-cycle stages; and considering environmental and economic effects. This paper provides an outline of each of the elements within this overall set of tools, and illustrates their use through combined application to a set of three case studies for transitions of households from traditional fuels to electric cooking, in different contexts: for urban households connected to the grid in Zambia; for mini-grid connected households in Tanzania; and for off-grid households in Kenya. This paper represents the first time this diverse range of approaches has been brought together.

The individual models and tools continue to be developed and applied in their own contexts by the respective groups, with more detailed specific outputs available. The models are applied to simulated communities – based on a variety of data – and as such the combined modelling does not provide definitive answers for the costs/benefits of eCooking in real locations. Instead, it demonstrates the importance of examining eCooking from multiple perspectives and illustrates the advantages of this multi-disciplinary working.

Appliance ownership from various surveys (principally from the Multi Tier Framework, ESMAP, no date)(Luzi *et al.*, 2019) informs a time of use profile. Adding to this the experiential data of how people cook from the cooking diaries, and taking into account lab based tests on the power consumptions of various appliance, load profiles are generated. The models of the timing of electricity use and cooking, grounded in empirical evidence, shows the important effects of diversity in when, and how, people use their appliances, such that the 'after-diversity' load added to the supply system is much lower than the connected capacity of devices.

The costs of appliances and resulting electrical consumption plus other system factors are included in a cost benefit model. This accounts for alternative fuels, and can present the cost comparison of the approaches, and in most case directly challenges the perception that electricity is expensive and illustrates the cost effectiveness of electricity (eg ESMAP, 2020a).

The load profiles feed into a network analysis. The network analysis shows that eCook can be accommodated to a significant extent on existing grids; even on mini-grids, some 15% of households can transition to a 'clean stack' of electric cooking plus LPG, using existing spare capacity in most networks.

Utilising the SimaPro tool for Life Cycle Assessment, with the Ecoinvent database, the models work together to assess the environmental impact. This is important because the burden of biomass cooking is often spoken about solely in terms of human health (Household Air Pollution) but it also has environmental effects on ecosystems not least its contribution to climate change and natural resources (not least deforestation). Cooking with charcoal is shown to have twice the environmental impact of firewood. The study confirms that eCooking can be cost effective and offer overall reductions in environmental impacts, especially compared to cooking with charcoal, but points out potential 'hotspots' of impacts, including in the production of power electronics and in distribution network infrastructure, guiding system designers.

Finally we offer some headlines from the three case studies:-

Zambia - On grid

While appliances total to an installed capacity of around 200W, after diversity effects in the timing of appliance use and household occupancy, the expected peak in daily load equates to 63 W per household. A transition to eCooking with a total of 2 kW of cooking appliances per household, after diversity effects in the choices of meals and occupancy, would more than double the total electricity use per day, however the aggregate (diversified) peak power from cooking will increase an average of around 500 W per household. The power network analysis for this case showed that the 50 kVA limit on the substation transformer was not breached, thermal limits not exceeded and the maximum voltage drop while serving peak demand is within recommended limits. Overall this confirms that high penetrations of eCook devices are possible, mainly due to network assets being over-rated compared to typical load conditions and in this sense the existing network is 'overdesigned'. With low electricity tariffs, eCooking in Zambia competes well with charcoal and LPG. The eCook results suggest that with the purchase costs of the cooking appliances spread out, average monthly bills would fall from around $8 per month of spend buying charcoal or $12 per month for LPG, to just $2 per month. The LCA results show that a switch away from charcoal would deliver improved environmental outcomes, with substantial improvements in every impact category. In conclusion, low load factors within LV networks deployed in Zambia, and low tariffs for electricity lead to great potential for adoption of electric cooking devices. Where these are substituting for charcoal, significant reductions in health, ecosystem and resource impacts would result, alongside considerable financial savings for households.

Tanzania - mini grid

Households are at tiers 1 to 2, and hence have only a few appliances: these appliances total to between 30 and 90 W per household. After diversity effects non-cooking electricity use averages to between 60 and 240 Wh/household per day. If 10 households transition to eCooking with a 1 kW EPC, after diversity effects in the choices of meals and occupancy, the total electricity use per day for the group of 88 households will increase by more than 50%. After diversity effects the peak of the aggregate cooking load is equivalent to only 400 W per eCooking household. Since it was evident that the mini-grid would not be able to support eCooking by every household, some initial analysis was done to define the scenario of 10 eCooking households. Hence it is not surprising that the full power system analysis shows that the mini-grid with its 6 kW inverter can support this level of eCooking. The analysis of voltage distribution also shows however that the installed distribution network is capable of supporting eCooking for all households, although it would then require upgrade of the PV and battery capacities. The mini-grid modelled for Tanzania has quite high tariffs, and hence cooking is relatively expensive. The eCook modelling however showed it could compete with LPG, and could be equivalent cost to charcoal in some circumstances. A 'clean fuel stack' of EPC plus LPG could offer an attractive package and a route into eCooking. However mini-grid tariffs are expected to fall, and based on the World Bank's projections it could become cost effective to transition to 100% eCooking. The environmental assessment shows that for charcoal users, any switch to electric cooking using a mini-grid will provide environmental improvement. The current reality is that mini-grids are designed without cooking in mind, and if some eCooking can be achieved using 'spare' capacity of the existing infrastructure, that will come with very low additional impacts. In conclusion, the sort of mini-grid supplying tier 1 and 2 energy access in Tanzania might well have capacity to support some limited eCooking, with low environmental impacts, and with manageable, and falling, costs.

Kenya - Solar home Systems

With no form of existing grid supply of electricity available, introducing eCooking for this sort of region requires installation of a complete power supply, with the case study assessing individual Solar Home Systems. The system size required follows the eCooking scenario: 100% eCooking (assumed to require a hotplate and an EPC) needs PV of around 600 W and a Lithium Iron Phosphate battery pack of just over 2 kWh installed; these fall to 200 W of PV and a 0.75 kWh battery for the 50% eCooking case, which uses just an EPC. Such systems incur considerable upfront cost. However the eCook modelling of the financial investment shows that third party financing through some form of bespoke PayGo or leasing business model would result in monthly costs to the user that are competitive with charcoal. Of particular interest is the finding that a 'clean fuel stack' of the smaller eCook system stacked with LPG for the balance of cooking would cost a similar amount to cooking everything with LPG alone. This approach would reduce local emissions through substitution of renewable electricity for some of the LPG, and bring convenience benefits for the user, through the automatic controls in an EPC, as well as reduction in trips for refilling LPG cylinders. However the installation of any of these eCook systems would also bring valuable co-benefits, providing access to electricity for non-cooking services alongside the transition to eCooking. When the impacts on human health, on ecosystems, and on resource use are aggregated, significant benefits are shown for SHS eCooking compared to use of charcoal and firewood. Surprisingly, the aggregate impacts compared to LPG and Kerosene are similar, although it must be noted the modelling does not include last mile transport impacts. The environmental analysis shows clearly that the supply chain impacts of power electronics can be significant, and this suggests that accurate system design and sizing is important. In summary, this case study has shown that standalone PV-battery systems, akin to large solar home systems, could bring access to modern energy for cooking, as well as non-cooking services, to off-grid households. Where households are paying for traditional biomass cooking fuels, eCooking systems can bring financial savings and reductions in health, ecosystem and resource impacts.

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1. Introduction

More than 2.8 billion people rely on some form of solid biomass for cooking (IEA IRENA UNSD World Bank & WHO, 2020), which leads to serious health impacts. Indeed, in a recent State of Access to Modern Energy Cooking (ESMAP, 2020b), the number of people who do not have access to modern energy cooking is at 4 billion. Efforts to realise the ambitions of UN Sustainable Development Goal 7, for “access to reliable, sustainable, affordable & modern energy for all by 2030” are intensifying, focused on electricity access but with increasing attention to modern energy for cooking.

Indeed access to electricity has made significant gains over the last 10 years. The number of people without electricity has fallen 770 million in 2019 (IEA, no date). Many of those gains can be found in developing Asia, and are in part due to the increasing urbanisation of the world. At this headline level, we can see that of the 2.8 billion relying on biomass for cooking (or the 4 billion without access to mecs), 2 to 3 billion people have some form of access to electricity but still cook with polluting fuels.

Alongside the Sustainable Development Goals, the world is increasingly aware of its need to mitigate Climate Change. The coming decade will see a significant push towards net zero carbon as countries set targets for 2030, 2040 and 2050. Part of this will be pivoting existing electrical infrastructure from fossil fuels to renewables, building on the cost effectiveness of large scale renewable energy and the opportunities for decentralisation of power generation. As grids become cleaner, the opportunity to utilise the infrastructure to provide ‘sustainable’ modern energy for cooking will be increased further particularly in Asia.

While access to electricity has improved significantly, some of the grids in emerging economies and on the edges of national grids can be described as ‘weak’. Households experience load shedding and voltage drops, and the addition of cooking as a load is often seen by policy actors as something that may further disrupt the working of the grid. In this paper we model ‘weak grids’ and illustrate that even in these situations there may be prospects for some level of electric cooking.

Beyond the national grid, the current scenarios for how full access to electricity might be achieved, particularly with the majority of the unconnected being in Africa and with the expected population growth, envisage more than 50% of the gains being made through stand-alone systems and mini-grids, rather than grid connection (IEA IRENA UNSD World Bank & WHO, 2020). There is, therefore, a good deal of interest and investment in mini-grids, joining ongoing national efforts for grid expansion and commercial activity in solar home systems.

Irrespective of electricity access infrastructure, electric cooking is one of the most promising options as a clean substitute for solid biomass. Electric cooking faces a number of barriers, including perceptions that it is generally too expensive, and that it is not feasible with anything other than a strong grid connection. These perceptions are outdated, and recent research and ongoing trials have demonstrated that electric cooking is attractive to many users and that it can be cost-competitive for households in all types of electricity access context (ESMAP, 2020a).

MECS has undertaken detailed work in a variety of locations across sub-Saharan Africa and in parts of Asia to understand, for example, local cuisine and cooking preferences and comparing the effects of cooking practices and appliance choices on energy use. Empirical data sets and insights have been produced, and research methods developed. In parallel, modelling of eCook options has been undertaken, using some of these data, but to date it has provided only a high-level view, using averages or ranges of values, and with relatively coarse time resolution in the analysis. The technical, economic and environmental performance of electric cooking compared to other options in any real location will depend on the intersection of a range of local factors, including what and how people cook, local availability and prices of fuels, the characteristics of their particular electricity supply (or the local weather patterns if a standalone eCook system is considered), how existing patterns of energy use vary across the day, and which types of electric cooking appliances are adopted, and which traditional fuels are commonly used. An important question is whether the existing electricity supply infrastructure (grid or mini-grid) has the ability to accommodate the additional energy use and peak power flows that would arise as eCooking is added on top of existing power uses. This depends on complex linkage of the technical energy and power flow capacities of the power generation and storage, the power flow ratings of the distribution network and also the nature of the energy uses: how the loads vary over time, in response to user activities.

Furthermore, in terms of environmental performance the existing analysis has only considered a narrow set of issues: comparing greenhouse gas emissions from electricity generation for eCooking with direct combustion emissions from biomass fuels. eCooking in any electricity access context will require considerably more capital equipment and supporting infrastructure than combustion of biomass fuels, and environmental impacts across the complete life cycle should be considered. This is particularly the important as climate mitigation rises on the policy agenda. It can be argued that environmental impacts associated with electricity infrastructure can be attributed to non-cooking uses, as these constitute the justification for universal access polices, however in this paper we consider them as part of the system that is supplying the modern energy cooking service. LPG is another modern energy cooking option, and similarly requires considerable infrastructure along its supply chain, and a life cycle approach to its impacts. Figure 1 gives an indication of the wide range of factors relevant to assessing options for meeting cooking needs.

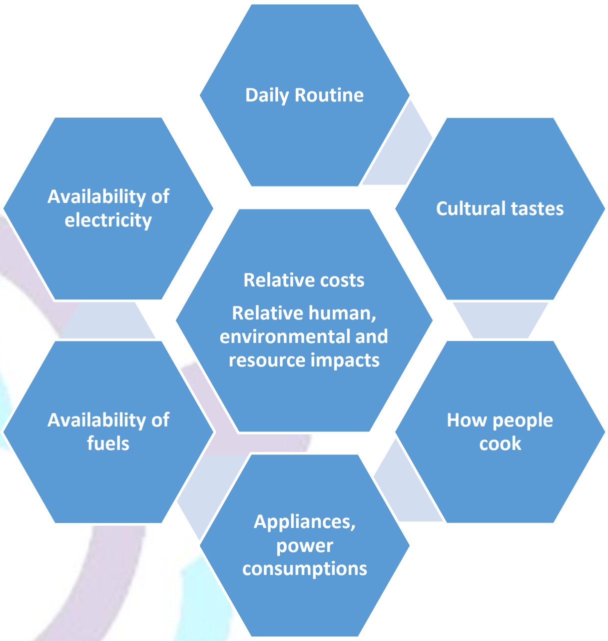

Figure 1 Factors in cooking choices

1.1 Outline of paper

Subgroups within the MECS programme's modelling theme have been addressing these different challenges, producing methods and tools which can provide a detailed analysis of specific situations, to make use of the growing body of empirical evidence. This work has and continues to be published by the individual subgroups. The current working paper reports on a parallel effort to bring the various strands of work together. The paper illustrates the level of detail and the range of factors taken into account in generating an understanding of the technical, economic and environmental impacts of eCooking. The case studies demonstrate how various stakeholder groups, such as utility companies, mini-grid developers, and environmental groups will be able to utilise the modelling as they engage with the clean cooking agenda.

1.2 Overview of the models/methods used

The overall aim of this collaborative modelling is to develop a set of tools and analyses that can represent the key impacts a transition from traditional fuels to electricity for cooking will have on the transitioning households, on the energy supply systems, and on the human and environmental impacts of the wider supply chains for the fuels and equipment required. The approach taken is to model a set of eCooking case studies, which investigate baseline non-cooking electricity loads, additional loads from eCooking, the associated electrical network impacts, and the life-cycle environmental impacts of the cooking and network infrastructures required.

The structure of the analysis for each case study has the following steps:

1. Develop the context and assumptions for each case study, including a range of household types within each
2. Gather data for the household types: non-cooking electricity use, cooking activities
3. Model the typical electricity load patterns for non-cooking and with eCooking added, for each household type, including appropriate measures of diversity in timing of loads
4. Perform electricity network analysis for the set of loads
    - If initial network analysis reveals supply constraints, either determine upgrade requirements or loop back to step 3 to reduce eCook uptake levels
5. Undertake a Life Cycle Assessment (from cradle to end of use) for the eCook appliances, fuels and electricity used and electricity supply infrastructure.

Section 2 presents details of the individual steps and models concerned.

1.3 Overview of the three cases studied

For this working paper, three case studies have been undertaken to illustrate the application of this suite of models. The cases are chosen to reflect a range of contexts in which eCooking will be taken up, across a range of countries. The cases are:

- Case 1: grid-connected households in urban Zambia
- Case 2: mini-grid connected households in rural or peri-urban Tanzania
- Case 3: off-grid households in rural Kenya.

Within each case study, the characteristics of the households concerned and the access they have to electricity are defined. The countries and access contexts of the cases are the same as three of the five case studies used in the ESMAP study of costs of cooking with Electricity (ESMAP, 2020a). Additional detail is required here about the households, as ESMAP (2020) applied only the one of the modelling approaches used in the present working paper, which considers only daily totals of energy use, and gives no attention to non-cooking services, capacity of infrastructure, or environmental impact. The ESMAP report explores a wider range of alternative scenarios for each of its five cases, for example eCooking with and without battery support, and 50% or 100% eCooking. The current multi-model study could replicate all of those scenarios, but to simplify demonstration of the added value of the multi-model approach, a limited set of illustrative cases are used.

Sections 3 to 5 present further details of the households in each case, and the results of the modelling and analysis of their transitions to electric cooking. First section 2 describes the individual models applied.

2. Individual modelling and assessment methods

The sections below provide an outline of the methods of analysis and models applied, with links to other reports or papers in which they have individually been described in greater detail. The outlines here are presented as generic methods: illustrations with real data are provided through the case study analyses in sections 3 to 5.

The structure of the analysis for each case study has the following steps:

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4. Perform electricity network analysis for the set of loads
    - If initial network analysis reveals supply constraints, either determine upgrade requirements or loop back to step 3 to reduce eCook uptake levels
5. Model the costs of cooking for households, using traditional fuels and after transition to eCooking
6. Undertake a Life Cycle Assessment (from cradle to end of use) for the eCook appliances, fuels and electricity used and electricity supply infrastructure.

The diagram in Figure 2 shows the linkages between the various models and data.

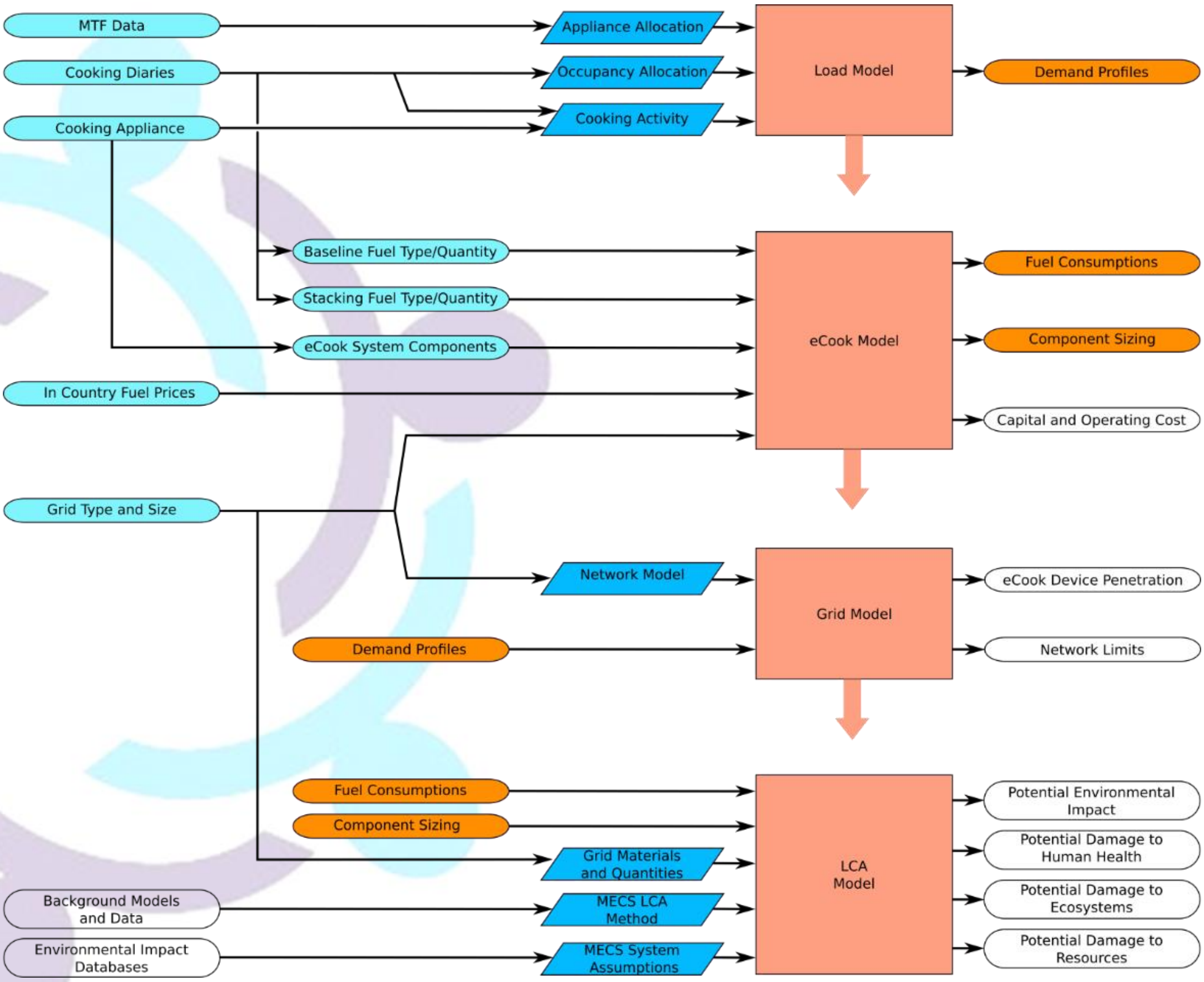

Figure 2 Combined models and linkages

The four main models are shown in boxes: *Load model, eCook model, Grid model* and *LCA model*. The broad arrows indicate the semi-sequential nature of the work: the *Load model* must be executed before the *Grid model* and the *eCook model* must be executed before the *LCA model*. The outputs of each model are indicated on the right side: where these form inputs to other models they are shaded orange.

Model inputs are given on the left as lozenge shapes: light blue shading indicates that these inputs are dependent on the *case study*. Where an input is taken from the output of another model the lozenge shape is shaded orange (e.g. *Demand Profiles*). Non-shaded lozenges indicate data that are not dependent on either the other models nor the *case study*.

Some of the inputs require a significant amount of interpretation to convert or synthesize data that are suitable for the models. These are indicated by blue trapezoids.

It is apparent from the diagram that the nature and details of the *case study* influence many of the model inputs, and hence the results will vary significantly between cases.

2.1 MECS household load modelling

An overall ambition of this collaborative modelling is to understand how the addition of electric cooking will change load patterns, and what impacts that might have on electricity supply systems. In broad terms, if the aggregate load on the network at a moment in time exceeds certain thresholds, technical performance will degrade and eventually the network will fail. As Richardson *et al.* (2010) point out, summing the individual maximum demands from each household over a period of time (say a day) gives the "maximum non-coincident demand". However in reality, the maximum for each household is likely to occur at a slightly different time and thus the maximum time-coincident demand of all households together is lower and is known as the "after diversity maximum demand" (ADMD).

To estimate the maximum diversified demand (and other important characteristics of how loads on the network change over time), data are needed on the full set of loads that are connected to the distribution network, including their magnitude and how those vary over time. To understand the impacts of adding electric cooking into household use, the baseline electricity loads for all non-cooking purposes are needed first, followed by the additional cooking loads (Lombardi, Balderrama, *et al.*, 2019).

MECS research into cooking takes a bottom-up approach, starting with the individual household cook and their preferences and practices, gathered for example through Cooking Diary studies (Leary *et al.*, 2019). As such, there is a growing dataset on household energy use for cooking. However to date there has been limited analysis of how cooking, and the energy use resulting, varies by time, although *Lombardi et al* have produced some work in this area (Lombardi, Balderrama, *et al.*, 2019 and Lombardi, Riva, *et al.*, 2019). MECS's primary focus is on understanding cooking activities and their impacts, but the boundaries of investigations are now widening, as the impacts of adding cooking are affected by the pre-existing level of non-cooking electricity use. Beyond MECS, there is an overall lack of publicly available data on residential load profiles in developing countries, although Mandelli et al have synthesized demand profiles based on interview data and the *LoadProGen* model (Mandelli *et al.*, 2016). However small scale metering studies are now growing in number as part of innovations in energy access, and the sort of modelling in this study should help make that more widely available.

2.1.1 Objectives and approach for load modelling

A new MECS household load model has thus been developed. The details of this are reported in Leach, Mullen and Wade (2020); a summary is included here.

The objectives for the load model were:

- a tool for creating fine time-resolution load profiles for electricity use for an individual household, and aggregations of multiple households, for cooking and non-cooking activities, and suitable for rural and urban users in MECS target countries;
- allowing variation in a wide range of parameter values to represent different user types and contexts;
- capture variability in loads (for more realistic representation, and to reflect diversity into aggregations)

The new MECS household load model has been developed by building on the structure of the existing "CREST Energy Demand Model", developed over a period of some ten years at Loughborough University to represent the electricity usage of the residential sector in the UK (Richardson et al., 2010). Recent versions of the CREST model have introduced features relevant to the UK context (eg building-integrated renewables) that are unnecessary complications for the proposed application here, and so an earlier version was used as the basis: version 1.0B.

Figure 3 shows the structure of the appliance use model, which includes cooking. A similar approach is used alongside this for lighting, influenced also by the external lighting levels by time of day. The model simulates 24 hours of operation. The diagram shows the model being used to represent "n" number of different households; in practice each run of the model represents one household; the parameters can be changed, and the model re-run multiple times to gather such a set of results. The active occupancy model has a time step of 10 minutes whilst the demand model has a time step of 1 minute.

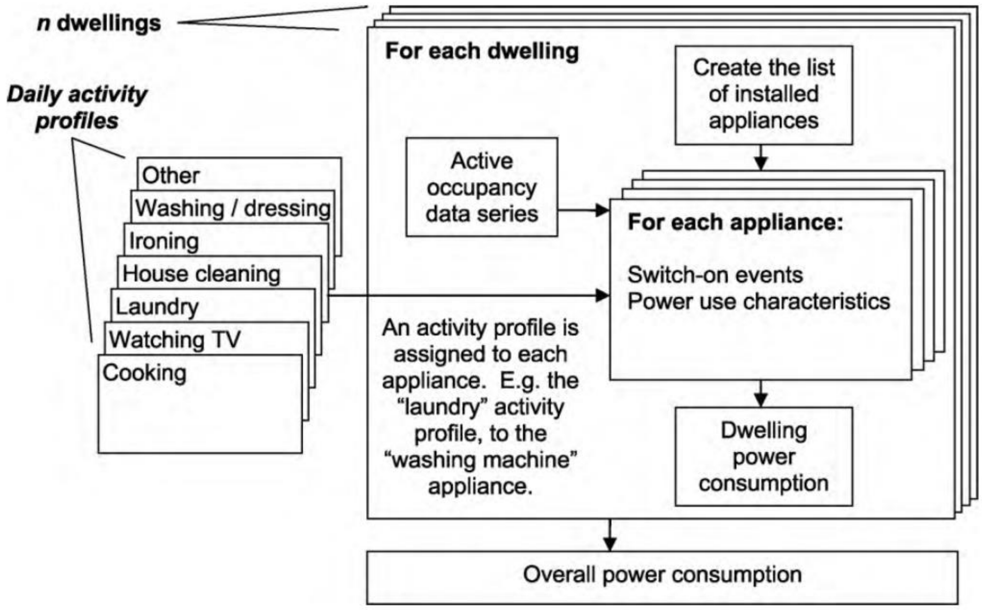

Figure 3 Electricity demand architecture of the CREST Energy Demand Model

Source: Richardson et al. (2010)

Throughout the model, probabilistic processes are used: for example, the probability of a particular activity taking place in any one minute time period depends on the number of active occupants determined for the household at that time. Most demands are related to appliances serving a particular activity type (such as cooking, ironing, watching TV) whilst appliances such as fridges, freezers and clocks operate irrespective of active occupancy.

The original CREST model was intended to represent the UK residential sector, with the combination of the various probability distributions that were calibrated such that running the model many times should lead to an aggregate load profile that approximates the observed load profile of the overall sector. As such, any one model run produces results which may be broadly representative of some sort of UK household, but the nature of that household changes fundamentally from one run to the next. For example, the ownership of appliances is assigned randomly, as is the pattern of occupancy. For MECS purposes, it was necessary to adapt the model so it could be controlled to represent a particular household type (e.g. with specified appliance ownership), whilst retaining probabilistic treatment of behavioural factors such as occupancy and appliance use. In addition, while the original CREST model includes a set of cooking devices as part of the overall modelling of appliance use, it does not offer sufficient control of the assumptions to be used for the sort of case study analysis of eCooking transitions intended here. As such a new cooking module was developed, described below.

2.1.2 Demand model process

The steps to simulate a single household for one 24-hour period are:

1. Specify the overall number of residents in the house
2. Specify ownership of appliances, with typical usage (average hours per day); specify light bulb ownership
3. Determine household occupancy patterns. Currently based on occupancies at meal times from cooking diary data; occupancy between meals is set at the lowest of the number of people at the meals either side
4. Run the electricity demand simulation (including both the lighting and appliance models)

The Lighting model: specify an external irradiance threshold at which lights might be used. For each bulb, cycle through each minute of the day: switch on bulb if outside illuminance falls below threshold chosen, AND if random condition met, weighted by the active occupancy. Once switched on, a bulb stays on for a duration selected randomly from within one of nine duration ranges, allocated randomly; or until active occupancy falls to zero (for example once everyone is asleep at night).

The appliance model: cycles through each appliance and for each minute time step may ‘start’ an appliance operating, based on a probability derived from the typical usage characteristics, and dependent on any occupancy requirements for that appliance. Appliance run time once started is subject to probability around a typical run time, and some appliances have a restart delay after use. Some appliances have bespoke power profiles once started: e.g. refrigerators which cycle on and off.

Once steps 1-2 have been undertaken to define the household’s characteristics, the occupancy simulation and the appliance and lighting models can be run (steps 3 and 4). Steps 3 and 4 can then be repeated multiple times to represent a set of similar households for that one 24-hour period, or to represent a series of days for the original household, with the probability processes introducing variability in occupancy and behaviours. Changes in household size, appliance ownership and cooking patterns can be introduced by undertaking steps 1 and 2 again, with changes in relevant parameters.

The model reports the load in each minute for lighting, appliances and cooking; as such, the household’s baseline load profile without eCooking can be readily compared with the additional loads that eCooking introduces.

Further details of the model processes can be found in (Leach *et al.*, 2020). The types of parameters and their values are illustrated in the three case study sections below.

2.1.3 Cooking model

A new sub model has been developed, following similar principles to the existing appliance model, but allowing greater control of cooking appliance characteristics and their use. An outline of the method used is given in Figure 4; each step shows the source of data. The results of this analysis are electricity loads for cooking for each minute of the day, which can be added to non-cooking loads to generate overall household load. The loads for multiple runs of the model can be added together to get overall load per minute for a group of households. These results are used for the power network analysis described in section 2.4. Note that the eCook model described in section 2.3 and the LCA in section 2.5 need only the daily totals of electricity use for cooking because time of day and probabilistic effects are not relevant to either of these models.

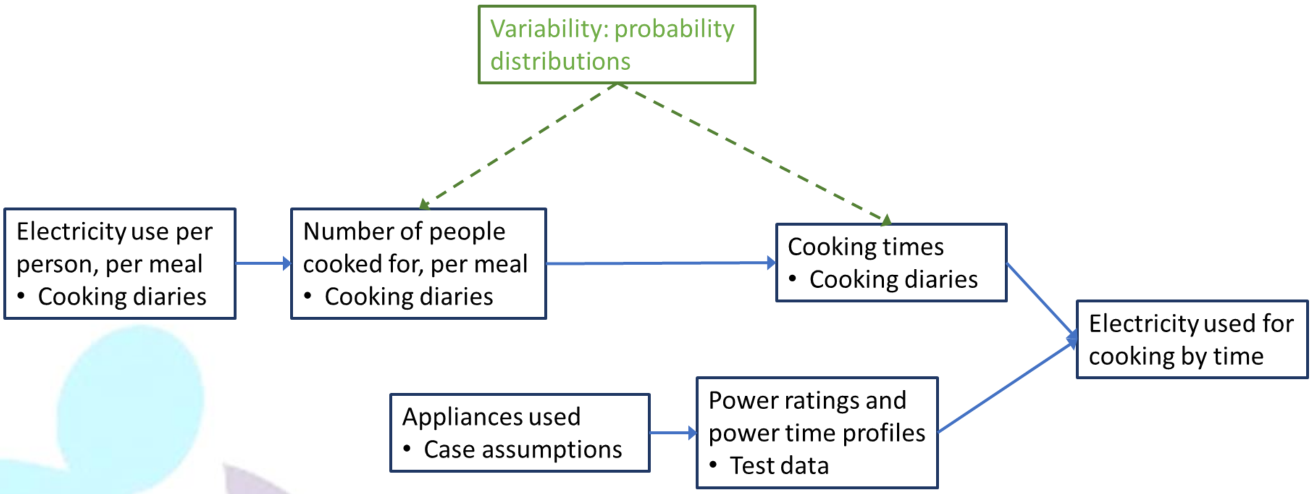

Figure 4 Outline of the MECS demand model for cooking

As for the overall demand model, the new cooking model is based on probability processes to introduce variability for key parameters, and thereby reflect diversity between households and uncertainty in natural processes. The cooking model uses a random draw for each minute to decide whether to start the appropriate eCook appliance within the relevant meal period, and once started it will operate with a specified power profile. As the figure shows, the variability is introduced to the household occupancy at meal times, and to the timing of the meals.

The meals eaten and associated cooking undertaken by households for each of the case studies are based on assumptions drawn from primary data gathered in cooking diary studies undertaken in each of the countries as part of the wider MECS programme and its forerunners, and statistical analysis of those. The specific assumptions for each case, and links to the source data, are given in the relevant parts of sections 3 to 5. Assumptions about the types of appliances used, and then the technical characterisations of them, are included in section 2.2.3.

2.2 Modelling appliance ownership, demand ratings and usage

The specific assumptions made about appliance ownership and use for the households included in the three case studies for this work are given in the relevant parts of sections 3 to 5. This section describes the assembly of a database of non-cooking electrical appliances, in terms of patterns of ownership and use, across the full range of energy access levels. These data are essential inputs for the MECS household load model described in the previous section.

To formulate and populate parameters for appliance ownership, usage (durations) and demand ratings the following reports and data were analysed:

- The Beyond Connections report (Bhatia *et al.*, 2015)
- Zambia MTF Electricity Survey, raw data (Energydata.info, 2020)

The Beyond Connections report provides the overall framework for describing appliance ownership and use by tiers of energy access; the MTF country surveys, of which the Zambia report (and associated data) is a good example, provide further detail. The analysis excludes eCook devices in order that non-cooking demand profiles could be modelled. By adding eCook devices separately to the MECS household load model a comparison could be made between demand profiles with and without the uptake of eCooking.

2.2.1 Demand ratings and appliance usage durations from Beyond Connections report

Demand ratings and usage durations values for several appliances were determined via inference from appliances, their power ratings and usage durations given in Bhatia and Angelou (2015). Further appliances were added to the list based on the report annex table A2.1 which cites several sources of appliance rating data. However, the annex does not give any information about the duration of use of the appliances and these values were estimated based on experience and indications in A2.1. Some appliances from the report were not included as they would not be expected to be found in the lower-income households at the focus for this work. Water heaters were excluded as an appliance as they can be regarded (at least in part) as a cooking appliance: eCook devices are not considered at this stage but are added into the model separately. The appliance choices are further discussed in a working paper on the MECS website (Mullen *et al.*, 2020). The appliances, their power ratings, usage durations are given in Table 1, by Tier level. The uppermost appliance values are inferred from the body of the report, whilst the lower two appliances are taken from Appendix 2 of the report. A list of the appliances that were not considered is given in Table 2 along with the eCook devices.

The load model is flexible and can accommodate any number of appliances, both low and higher-powered devices. As the lists here show, for the current study attention has been focused on households in the lower tiers of energy access, reflecting the example cases to be explored.

Table 1 Appliance power, duration & Tier level, inferring from Bhatia and Angelou (2015)

Appliance	Tier 1			Tier 2			Tier 3			Tier 4			Tier 5		
	Watts	hours /day	Min. annual consumption (kWh)	Watts	hours /day	Min. annual consumption (kWh)	Watts	hours /day	Min. annual consumption (kWh)	Watts	hours /day	Min. annual consumption (kWh)	Watts	hours /day	Min. annual consumption (kWh)
Task Lighting	1	4	1.5	2	4	2.9	2	4	2.9	2	8	5.8	2	8	20
Phone Charging	2	2	1.5	2	4	2.9	2	4	2.9	2	4	2.9	2	4	2.9
Radio	2	2	1.5	4	4	5.8	4	4	5.8	4	4	5.8	4	4	5.8
General Lighting				12	4	17.5	12	4	17.5	12	8	35.0	12	12	52.5
Air Circulation				20	4	29.2	40	6	87.6	40	12	175.2	40	18	262.8
Television				20	2	14.6	40	2	29.2	40	2	29.2	40	2	29.2YU1
Food Processing							200	0.5	36.5	200	0.5	36.5	200	0.5	36.5
Washing Machine							500	1	182.5	500	1	182.5	500	1	182.5
Refrigerator										300	6	657.0	300	6	657.0
Iron										1100	0.3	120.5	1100	0.3	120.5
Air Conditioner													1500	3	1642.5
Extended Appliance list from Appendix 2															
Computer				70	2	51.1	70	4	102.2	70	4	102.2	70	8	204.4
Hair Dryer[1]										1200	0.1	43.8	1200	0.1	43.8

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[1] Estimated daily duration

Table 2 Appliances from Beyond Connections report that were not included

Appliance	Tier 1			Tier 2			Tier 3			Tier 4			Tier 5		
	Watts	hours /day	Min. annual consumption (kWh)	Watts	hours /day	Min. annual consumption (kWh)	Watts	hours /day	Min. annual consumption (kWh)	Watts	hours /day	Min. annual consumption (kWh)	Watts	hours /day	Min. annual consumption (kWh)
Extended Appliance list from Appendix 2 (not included)															
Printing				45	n/k	n/k	45	n/k	n/k	45	n/k	n/k	45	n/k	n/k
Water Pump[1]							500	0.2	n/k	500	0.2	n/k	500	0.2	n/k
Air cooling							240	1	n/k	240	2	n/k	240	3	n/k
Water Heating													3500	1	638.8
Room heaters													n/k	n/k	n/k
eCook Devices (not included)															
Rice Cooker							400	n/k	n/k	400	n/k	n/k	400	n/k	n/k
Electric Toaster										1000	n/k	n/k	1000	n/k	n/k
Microwave										1250	n/k	n/k	1250	n/k	n/k
Electric Stove[2]										1500	n/k	n/k	1500	n/k	n/k

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[2] Burner/hotplate only

2.2.2 Appliance allocation to households

Data from the Zambia MTF surveys was used to assess the most common appliances in households by creating an ordered list of mean number of appliances per household, as described in the following.

The MTF survey data for Zambia (Energydata.info, 2020) was analysed using a *Python* script to create a model of appliance ownership. According to the MTF Survey report for Zambia almost all urban households are either in Tier 0 (no connection) or Tier 5 in terms of *Capacity*[3], see Table 3. Therefore the analysis of appliances only considers grid connected households. Note that although 74.8% of urban households are considered to be in Tier 5 for *Capacity* , the proportion of urban households in Tier 5 in the full MTF evaluation is only 41.9% since this accounts for the Tier scores under other categories such as *availability, quality, reliability, quality, formality* and *safety of supply*. The Python script takes data from the MTF survey and processes it with the following steps:

- remove any bad data (number of appliances is negative, or not-a-number)
- filter for urban households only
- filter for grid-connected households only
- filter for households with no electric cooking appliances, in order to include non-eCooking households

The resulting list was ordered by the mean number of appliances per household. Since the list was filtered for non-eCooking households only, the list does not include: microwave oven; electric food processor/blender; rice cooker; nor electric hot water pot/kettle. This list was used to create two groups: one with only the most common appliances and another which also had some less common appliances. The latter group contains all the appliances in the former group. Appliances with a mean ownership of < 0.017 per household were not considered. This is shown in the four leftmost columns of Table 4. The shading of the most common and next most common appliances indicates two groupings of appliances that are used later in the eCook modelling work. The groupings are:

- *Group 1*: most common appliances from Incandescent Light Bulb to Refrigerator
- *Group 2*: larger set of most common appliances from Incandescent Light Bulb to Hair dryer

Table 3 MTF Tier levels for Zambia

Zambia		Tier 0 (%)	Tier 1 (%)	Tier 2 (%)	Tier 3 (%)	Tier 4 (%)	Tier 5 (%)
Capacity	National	59.3	2.2	0.7	-	-	37.7
	Urban	*(24.2)*	0.6	0.4	-	-	74.8
	Rural	91.2	3.7	1.0	0.1	-	4.1

Since the appliances from Bhatia and Angelou (2015)(Table 1) are different to those in the MTF survey data, a mapping between the two was developed, as shown in the third column from the right of Table 4. Since some appliance categories in this column belong to more than MTF Data appliances the mean number of appliances per household is different. The calculation of sum, weighted mean and standard deviation for the two groups of appliances is shown is shown Table 5. Appliances with more than one MTF appliance category are indicated with shaded cells. For example, Group 2 has MTF appliances *Regular mobile phone charger* and *Smartphone charger* which are both mapped to *Phone Charging*.

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[3] Based on estimates of household appliance usage

Table 4 List of processed appliance MTF survey data, excluding cooking appliances

Appliance in Zambia MTF Data	**Total number of appliances**	**Mean number of appliances per household**	**Standard deviation of number of appliances per household**	**Mapping to appliance categories from Table 1**	**Group 1**	**Group 2**
Incandescent Light Bulb	1076	1.490	2.485	Task Lighting	✓	✓
LED Light Bulb	859	1.190	1.960	Task Lighting	✓	✓
Regular mobile phone charger	817	1.132	1.189	Phone Charging	✓	✓
Compact Fluor. Light (CFL) Bulb	597	0.827	1.771	General Lighting	✓	✓
Electric Iron	482	0.668	0.486	Iron	✓	✓
Radio/CD Players/sound system	445	0.616	0.556	Radio	✓	✓
Regular Colour TV	429	0.594	0.550	Television	✓	✓
Refrigerator	412	0.571	0.530	Refrigerator	✓	✓
VCD/DVD	357	0.494	0.573	Radio		✓
Smartphone charger	354	0.490	0.917	Phone Charging		✓
Fluorescent Tube	337	0.467	1.120	General Lighting		✓
Fan	266	0.368	0.494	Air Circulation		✓
Flat colour TV	183	0.253	0.454	Television		✓
Freezer	177	0.245	0.449	Refrigerator		✓
Torch/flashlight/lantern	135	0.187	0.529	<none>		✓
Computer	40	0.055	0.252	Computer		✓
Hair dryer	12	0.017	0.128	Hair Dryer		✓
Black & White TV	9	0.012	0.144	Television		
Electric sewing machine	7	0.010	0.134	<none>		
Air Conditioner (AC)	6	0.008	0.117	Air Conditioner		
Electric Water Pump	5	0.007	0.098	(Water Pump)		
Space Heater	3	0.004	0.064	(Room heaters)		
Washing machine	3	0.004	0.064	Washing Machine		
Solar based water heater	2	0.003	0.053	<none>		
Electric water heater	2	0.003	0.053	(Water heating)		
Indoor Air cooler	2	0.003	0.074	(Air Cooling)		

Table 5 Appliance ownership data, by Group 1 and Group 2

Beyond Connections appliance categories	Group 1				Group 2		
	sum	mean	std		sum	mean	std
Task Lighting	**1935**	**1.357**	**2.272**		**1935**	**1.357**	**2.272**
Phone Charging	817	1.132	1.189		**1171**	**0.938**	**1.151**
General Lighting	597	0.827	1.771		**934**	**0.697**	**1.576**
Iron	482	0.668	0.486		482	0.668	0.486
Radio	445	0.616	0.556		**802**	**0.562**	**0.566**
Television	429	0.594	0.550		**612**	**0.492**	**0.546**
Refrigerator	412	0.571	0.530		**589**	**0.473**	**0.529**
Fan	-	-	-		266	0.368	0.494
Computer	-	-	-		40	0.055	0.252
Hair Dryer	-	-	-		12	0.017	0.128

2.2.3 Cooking fuels and appliances

Electric cooking appliances are modelled as partially or fully replacing traditional fuels (e.g. charcoal and firewood), but potentially also substituting for LPG. The following provides the assumptions on baseline cooking energy use, and then the details for the eCook appliances considered. The cooking practices themselves are described in the individual case study sections. As mentioned in the previous section, attention is given in this study to lower tiers of energy access, and hence for the eCooking scenarios attention is focused on a limited range of appliances, capable of delivering the core cooking services. A wider range of devices (toasters, kettles, coffee machines etc) could be added for future work.

2.2.3.1 Fuel and electricity used for cooking

The use of traditional fuels for cooking is based on cooking diaries data; the original data can be found in the cooking diaries reports for each country (Leary, Scott, Numi, *et al.*, 2019; Leary, Scott, Sago, *et al.*, 2019; Leary, Scott, Serenje, *et al.*, 2019). Analysis for ESMAP (2020) made use of these data to create a set of scenarios to represent the traditional fuel or electricity needed for cooking in a range of countries, for both 100% of cooking using each energy source, or for fuel stacking. The present modelling uses the same assumptions for the cooking energy required, although it takes this further by introducing the diversity in numbers cooked for and timing of appliance use. (Leary, Scott, Numi, *et al.*, 2019)

The cooking energy assumptions are given in Table 6: these are used for both the MECS household load model (section 0) and the eCook model (section 2.3). The values for 100 percent of cooking using that energy type are average from the measured fuel or electricity use in the cooking diaries studies. The energy use for 50 percent cooking are modelled: for traditional fuels, 50% cooking is assumed to use 50% of the fuel quantity. For eCooking, the 100% electric cooking was observed to be undertaken using a mixture of inefficient and high efficiency appliances (notably hotplates and Electric Pressure Cookers). The 50% eCooking scenario reflects use of an EPC only, for cooking suitable long/slow dishes, with the balance of cooking undertaken with the baseline traditional fuel. As such 50% eCooking uses only one third of that for 100% eCooking. See ESMAP (2020) for further discussion of this method.

Table 6 Measured energy use for cooking per day
Note: Values are normalized to a 4.2 person household

	Firewood (kg/HH)		*Charcoal (kg/HH)*		*Kerosene*		*LPG (kg/HH)*		*Electricity (kWh/HH)*	
Country	*100 %*	*50 %*	*100 %*	*50 %*	*100 %*	*50 %*	*100 %*	*50 %*	*100 %*	*50 %*
Kenya	3.50	1.75	1.75	0.87	0.25 kg/HH (0.31 litres)	0.12 kg/HH (0.15 litres)	0.23	0.11	1.92	0.64
Tanzania	3.50	1.75	1.75	0.87	n.a.	n.a.	0.33	0.16	2.06	0.68
Zambia	n.a.	n.a.	1.04	0.52	n.a.	n.a.	0.17	0.08	0.87	0.29

2.2.3.2 eCook options considered

The MTF survey process and reports includes a set of electrical cooking appliances, as shown in Table 2. However these options are not sufficient for the present purposes: for example 'Electric stove' as a category does not differentiate between one and two ring hotplates and upright hob/oven combinations. There is also no category to represent Electric Pressure Cookers EPCs. As such, the MTF cooking appliance categories were not used for this work. The appliances of interest to the MECS programme are discussed extensively in ESMAP (2020). The focus for the present work is on hotplates and EPCs. Hotplates are able to substitute for all of the cooking processes traditionally performed using charcoal or firewood: they are a flexible route to electric cooking, but they are not particularly energy efficient. An alternative to a hotplate is an induction stove, which may be a little more efficient. Hotplates are used here, to maintain compatibility with the eCook modelling undertaken for

ESMAP (2020), but the load model could be used to explore the difference that substitution by induction stoves might make in terms electricity use. Note that some induction stoves also have a lower power factor than a resistive heater (eg a hotplate), meaning they will cause higher reactive power flows, leading to greater efficiency losses in the network. If induction stoves are included in the load modelling then particular attention would also need to be paid to their influence in the associated power network analysis.

The Electric Pressure Cooker can cook many dishes with high efficiency and also quickly and cleanly. Kitchen laboratory experimentation and experience in real households shows that EPCs are technically capable of cooking the majority of dishes: estimated to cover 90% of the typical Kenyan cuisine for example. In practice cooks typically settle down to cooking around half of the dishes in the EPC and the remainder using other appliances: eg a hotplate or fuel stacking with their traditional energy source (Leary, Scott, Numi, *et al.*, 2019).

The cooking scenarios for the cases in this work are therefore defined as:

- 100% traditional fuels used for cooking
- 100% eCook, using a combination of hotplate and EPC
- 50% eCook using an EPC and 50% use of the traditional fuel

2.2.3.3 Characterisation of eCook appliances

Most forms of cooking involve an initial period at high power, for frying and/or bringing food up to the boil, followed by a period at lower average power, e.g. for simmering. Hotplate designs vary widely, with some responding to the user "turning power down" by modulating output through switching different combinations of heating coils in and out, controlled by a switch with a finite number of settings. However, another common approach is to vary average output by switching full power on and off, with the heating period controlled by an 'Infinite switch' or 'Simmerstat'. There is little published evidence about hotplate cycles and the effective power input will vary widely, with the quantity of food being cooked, the characteristics of the pot used, whether a lid is used and the cook's preferences. For the present study the assumed cycle takes the average power output to 50% of maximum.

For an EPC, there may be a period of open-lid frying, during which full power is applied until the device reaches a set temperature (typically between 120 and 140 deg.C), and then cycles power on and off to maintain that temperature. When the lid is closed the EPC continues at full power until the internal pressure reaches its operating level. Power then drops to zero, until the internal pressure drops to a lower threshold, at which point power is re-applied.

Both the hotplate and EPC are modelled in the same way, with an initial period at full power (termed "pre-heat") following by control to lower the effective power output by cycling between full and zero power. The specific parameter values for durations and power levels can be set in the load model. The duration of on and off periods for the EPC are derived from test data reported in Monk (2020). For the current study, the power cycling expected for any initial frying is not taken into account.

For both appliances, "Quick" and "Long" cook versions of the overall cooking cycle are defined. These are used to reflect the cooking needs for different food types, from frying to long simmer for the hotplate, and for foods requiring brief cooking to long tenderisation for the pressure cooker.

Analysis in the various cooking diaries studies has shown that total energy use to cook a meal scales almost linearly with the number of people cooked for. This finding is utilised here to represent the diversity in cooking loads arising from variations in household occupancy for meals. The proportionality factor is introduced to allow the model user to explore cases where total energy used to cook a meal does not scale one to one with the number of portions cooked.

$$Elec.use\ per\ meal = No.of\ people \times Avg.measured\ elec.use\ per\ person \times proportionality\ factor$$

To calibrate the pattern in loads caused by the pre-heat period and then on/off cycling to the varying numbers cooked for, use is made of EPC lab tests reported in Monk (2020). The time and energy spent by an EPC in each cooking phase was measured, with the EPC containing from 1 litre to 5 litres of water. The results show that the cycling (or 'cooking') phase remains almost constant, regardless of the volume cooked: the 'off' periods last as long as it takes for the internal pressure to fall to the minimum level, and the heat losses are almost independent of volume being heated. The pre-heat phase however increases in time and electricity use almost linearly with volume heated, since much of this phase is simply about raising the contents to the operating temperature. The lab tests show that the proportion of electricity used in the pre-heat phase varies from 70% to 88%, and so the preheat phase is particularly important.

To progress from the overall electricity used for the meal:

$$Elec.use\ in\ cycling = No.of\ cycles \times length\ of\ 'on'\ phase \times Rated\ power$$

$$Elec.use\ in\ preheat = Elec.use\ for\ meal - Elec.use\ in\ cycling$$

$$Time\ in\ preheat = \frac{Elec.use\ in\ preheat}{Rated\ power}$$

As mentioned, equivalent empirical evidence on hotplate cycling has not been found, and this extends to a lack of data on the pre-heat phase. The efficiency advantage of the EPC comes partly from its insulation, which reduces thermal losses, and hence the EPC uses the majority of its total cycle energy pre-heating from cold up to temperature. A cooking pot on a hotplate will have much greater thermal losses, especially once the pot's contents are up at temperature. As such, the share of total cooking energy expended in the 'pre-heat' phase will be lower than for the EPC: this is assumed to be 50% (compared to the typical 80% for the EPC).

Table 7 summarises the assumptions made for the eCooking appliances; when combined with the calculated electricity use for a particular meal, the timing of the pre-heat and on-off cycles is determined. Once the appliance is called to 'start' in a certain minute by the load model, the cycle proceeds with these timings.

Table 7 Electrical cooking appliance assumptions

Appliance	Power (W)	Proportion of energy in pre-heat (%)	Cycling on-time (min)	Cycling dwell (min)	No. of cycles (Quick cook)	No. of cycles (Long cook)
Hotplate	1000	50	2.00	2.00	5	14
EPC[4]	1000	70-88	1.00	7.00	2	6

2.3 eCook system design model

The eCook model was developed to undertake outline design of the eCook system needed to meet given cooking requirements. It has been refined through a series of projects since 2015, and applied most recently for the ESMAP (2020) Cooking with Electricity: A Cost Perspective report. Through the ESMAP project, the initial use of the model for off-grid households, and thus eCooking using solar PV charging batteries, has been broadened,

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[4] Based on Monk (2020)

and it can now represent grid- and mini-grid connected users too, with and without battery support. Full details of the model can be found in Leach *et al.* (2019).

2.3.1 eCook model description

The model is designed to explore alternative ways to deliver the 'cooking service' currently delivered by traditional stoves and fuels; as such, the functional unit is not cost per unit of electricity delivered from an eCook system, but is related to the cost per meal, or cost for household cooking per day or per month. The current model has a detailed treatment of cooking practices based on primary data, characterisation of the costs of the major components based on learning rates (e.g. see Rubin *et al.*, 2015), and an empirically-based model for battery degradation, capturing the high current drain and harsh operating conditions for this application.

Figure 5 shows the structure of the model. The energy needs for cooking (green box) define the requirements of one or more electric cooking appliances and a matching inverter (if required). The eCook system (light blue boxes) is sized to meet a user-defined fraction of this total cooking demand, with the balance met from a specified traditional fuel (brown box).

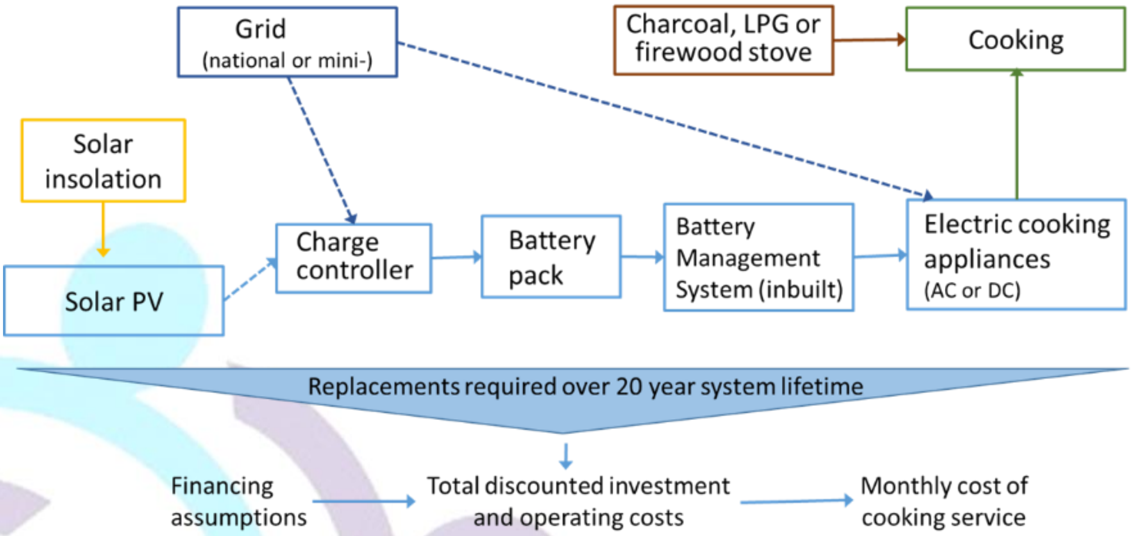


Figure 5 eCook model structure

The required battery storage capacity can then be determined, along with a suitable charge controller. Finally, the solar PV can be sized, based on the daily need for battery charging and the solar insolation available (yellow box). Alternatively, for an on-grid or mini-grid applications, the load on the grid is calculated (dark blue box). The battery, solar PV (if used) and balance of plant are sized for daily load balancing. A user-defined factor is included for oversizing of storage to allow for both unusually high cooking demands and/or reduction in grid or PV supply input, for example so that the system can 'ride through' an unusually cloudy day without the battery fully discharging. Power losses are modelled in the wiring (typically 5%), the charge/discharge cycle (typically 10%) and in the inverter (if used).

Appropriate information is thus needed on each of the elements in this system, firstly for the system design and sizing, and then for costing. The individual model elements are intended to be generic placeholders representing categories of equipment (eg 'Battery pack' could in practice represent a set of Lithium Ion batteries of some particular chemistry, or Lead-Acid batteries). The detail of each element is then part of defining the specific case to be analysed. Equally, the characteristics of any particular piece of equipment may change over time or by place, and again the model is intended to represent the generic system, with detailed value for the parameters of each element captured in case applications. For example, Lithium Ion battery performance is improving and costs are reducing, with technological learning and through economies of scale; the model is applied using data intended to represent technology performance and costs for a given point in time. Similarly the Financing assumptions follow the business model to be represented in a case analysis. The overall result of the model is comparison of the costs of cooking per month between the eCook system and a baseline of traditional fuel purchases.

2.3.2 Application to the three cases

The eCook model operates at the level of daily demand for electricity for cooking. As such the sum of the electricity used for cooking is calculated from the MECS household load model and forms the input to the eCook model. For cases 1 (grid) and 2 (mini-grid) in this work, household-level battery support is not considered, and the eCook model will simply facilitate costing of the cooking appliances required, calculation of electricity costs from grid and mini-grid respectively, and the costs of traditional fuel required for stacking or as the baseline. For case 3 (off-grid solar home system (SHS)) the eCook model is used to size and cost the complete PV-battery eCook system needed.

ESMAP (2020) and Leach, Mullen and Wade (2020) provide fuller descriptions of the model, and thus the basis of cooking costs that result. There are many parameters, and hence sensitivity analysis can be undertaken to explore the influence of different assumptions and data inputs. For the present multi-model study, a reduced set of assumptions are made, so that the other models can be run for matching scenarios.

Two choices for the scenarios run here are of particular importance. Firstly, the eCook model is run here to estimate costs for eCooking implemented in 2025 only. The ESMAP (2020) study includes 2020 and 2025, with the main differences being that eCook component costs are expected to reduce gradually over time, and the prices of traditional fuels are expected to increase (at 3% per year). Secondly the eCook model calculates monthly costs to the household on the basis of choices on how initial capital costs (and costs of equipment replacement required over time) are financed. ESMAP (2020) explores 'utility financing' in which capital costs are financed over a 20 year repayment period, and a 'PayGo'-type business model, as used for solar home systems, but with a 5 year repayment period. The present study includes just the 5 year financing option: this leads to higher monthly costs to the user, but is arguably a more realistic way for eCook to be implemented in the near term.

2.4 Electrical infrastructure network model

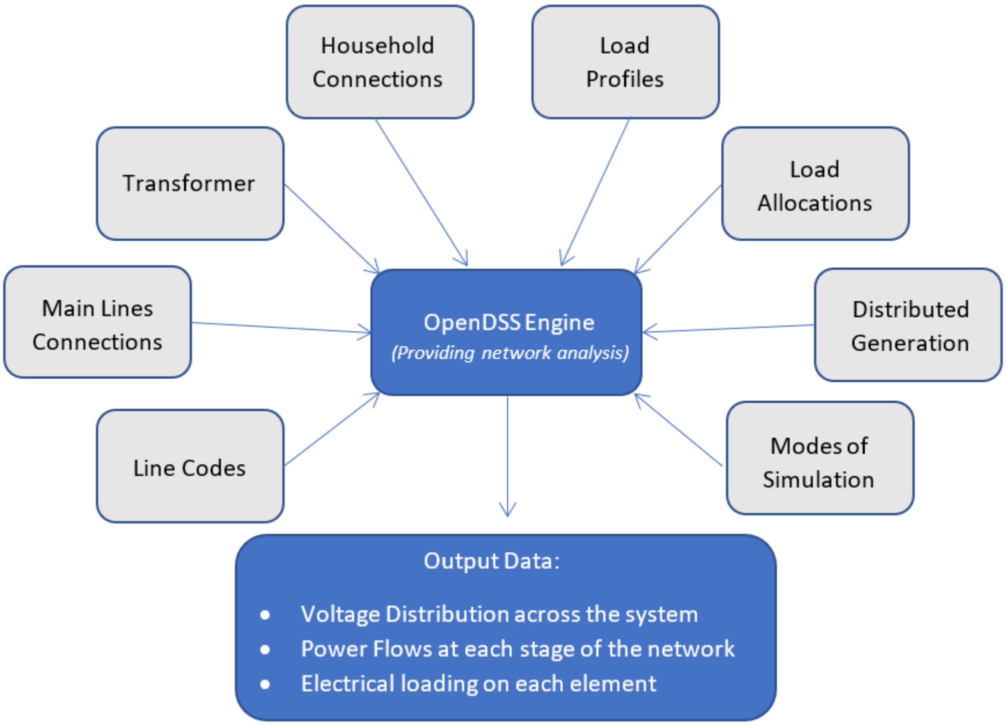
Models for Low Voltage (LV) and mini-grid networks have been developed based on typical systems infrastructure providing access to electricity in the Developing World. The models were constructed in OpenDSS (EPRI, 2021) – an electric power Distribution System Simulator for supporting distributed resource integration and grid modernisation efforts. Detailed analysis of the inclusion of eCook applications has been presented in the *Impact of New Electric Cooking Appliances on the Low Voltage Distribution Network and Off-Grid Solar Micrografids* report available on MECS website (Soltowski *et al.*, 2020). The studies undertaken primarily focus on networks with the following summary specification:

- **LV distribution networks (downstream of secondary substations):** LV network models were specified primarily based on literature outlining design guidance, standards and practices, with input from a Power System Planning Engineer from the Electricity Supply Corporation of Malawi (ESCOM). As such, the system consists of 79 households supplied by four feeders, each connecting between 17 and 22 households via 50mm^2 Aerial-Bundle Cable (ABC) and power transformer capacity (stepping down voltage from 11 kV to 220V) was set to 50 kVA.
- **Rural off-grid mini-grids with centralised generation and storage:** The mini-grid network models were designed using data available from Powergen mini-grids in Kenya and Tanzania. The parameters selected for the mini-grid were based on publications provided by Powergen, the incumbent utility grid operator

(Schreiber, 2020 and Williams *et al.*, 2017). The system provides electricity for 88 households over 50 mm^2 ABC distribution cables and 16 mm^2 service lines. The system is supplied from a 6 kW inverter.

The outcomes of the studies illustrate three of the principal technical challenges associated with the adoption of electric cooking on existing networks: thermal limitations of the cables, maintaining adequate voltage profile distributions and transformer/power inverter requirements.

The models can be readjusted according to users' requirements and can thus be repurposed for further analysis of the existing or equivalent systems. As such, individual investigations presenting the performance of each LV/mini-grid network after adoption of electric cooking (eCook) demand can be validated independently using existing OpenDSS scripts for LV/mini-grid networks (see Figure 4).


Household Connections

Load Profiles

Transformer

Load Allocations

Main Lines Connections

OpenDSS Engine
(Providing network analysis)

Distributed Generation

Line Codes

Modes of Simulation

Output Data:

- Voltage Distribution across the system
- Power Flows at each stage of the network
- Electrical loading on each element

Figure 6 Network Analysis Tools Developed in OpenDSS

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

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

2.5 Environmental impact

An environmental assessment was carried out for each case study to complement the results from the economic and load design. The sections below outline the approach taken for the environmental assessment. The study is conducted following the principles of BS/EN ISO 14040 and 14044 and other good practice systems.

2.5.1 Goal and scope of environmental assessment

The goal of the assessment was to provide insights into the effects of using different cooking fuels and devices in the different case study locations. The study was not intended to make comparisons between competing cooking devices. The study will provide policy makers with environmental information to raise awareness of the multitude of competing factors that must be considered when assessing environmental impact, identify in generic terms issues with different fuel/cooking device systems and progress the understanding of the environmental impacts resulting from a shift to clean cooking scenarios.

As described in section 1.3, three cases are assessed; grid powered eCook in Zambia, a PV powered mini-grid in Tanzania and an autonomous solar home system (SHS) in Kenya. The cases are not compared with each other, rather, each clean cooking option is compared against the traditional cooking methods as found in the relevant region.

2.5.2 Functional Unit(s)

The functional unit is cooking energy requirement per household per day. For the mini-grid case study in Tanzania, two approaches have been used; cooking only and cooking with associated lighting and other electrical services, to explore different options for how mini-grid impacts might be allocated.

2.5.3 System Boundaries

The study follows a *cradle to use* LCA approach. No end-of-life (EoL) data has been incorporated into these results, and so it is likely that actual impacts are potentially worse than represented here. This is due to the limited EoL recovery, reuse and recycling facilities in the areas covered by the case studies. Thus the results presented here should be understood in this construct. EoL actions may increase total impact, if waste electrical components are badly managed, or may reduce environmental impact, if products/components/materials are appropriately collected and returned to the economic system.

The following life cycle stages are included within the system boundaries for each case study:

- Raw material extraction and processing (for associated hardware and infrastructure)
- Transport for raw materials to component manufacture (where actual distances are not known, estimates from literature and global averaged transport distances have been used)
- Product manufacture
- Use of the product over life (includes fuel consumption)

The following life cycle stages have been excluded:

- Transport between place of component manufacture and place of use
- End of life actions

A flow diagram representing the system for each case studies is provided in the relevant section.

2.5.4 Modelling guidelines for allocation and recycling

Allocation on a mass basis has been employed for this study. Impacts from materials processing are allocated 100% to initial use, meaning that recycled materials only carry the burden of their recycling, with no added percentage from the impact of the first use.

2.5.5 Methods

The LCA model was developed using SimaPro Version 9 software. There are three stages where LCA data can be analysed:

- the inventory data, useful in understanding quantities of material (kg) and energy flows (MJ)
- midpoint impact categories (problem oriented);
- endpoint impact categories (damage oriented).

The midpoint categories are problem oriented, with relatively low uncertainty values. However, the high number of midpoint categories can make results confusing and create difficulties in determining robust conclusions. To combat this, they are multiplied by damage factors to create three endpoint categories (damage oriented). This introduces higher levels of uncertainty, but allows for easier interpretation. The impact assessment methods used were ReCiPe Midpoint, hierarchical viewpoint and ReCiPe Endpoint, hierarchical viewpoint[5]. These methods were chosen as there is no specific method available for SSA, and they are globally recognised with an international track record of use in the community and governments.

The midpoint impact categories covered are:

- climate change;
- ozone depletion;
- terrestrial acidification;
- freshwater eutrophication;
- marine eutrophication;
- human toxicity;
- photochemical oxidant formation;
- particulate matter formation;
- terrestrial ecotoxicity;
- freshwater ecotoxicity;
- marine ecotoxicity;
- ionising radiation;
- agricultural land occupation;
- urban land occupation;
- natural land transformation;
- depletion of fossil fuel resources;
- depletion of mineral resources;
- depletion of freshwater resources.

Of these, the following categories are considered to be particularly relevant to the MECS programme:

- climate change;
- particulate matter formation;
- human toxicity.

Normalised Midpoint impact category data values are calculated by dividing the midpoint impact results by the equivalent impact from all sources for the World (using data for 2010); the unit is the Eco-Indicator point (Pt), normally reported as milli-point (mPt). The normalised results thus give a sense of the relative significance of the additional impact associated with the eCook system assessed, compared to other sources of that impact. It is the comparison of values between different options and between different impacts that is most meaningful, rather than the absolute value of any impact itself.

The endpoint impacts covered are:

- human health (disability adjusted life years lost in the human population);
- ecosystem quality (number of species lost integrated over time);
- resources (surplus cost in USD).

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[5] https://support.simapro.com/articles/Manual/SimaPro-Methods-manual

There is still uncertainty in some midpoint impact categories, and this, alongside the fact that the impact assessment reflects potential, not actual, impacts should be taken into account when interpreting the LCA results. Any real damage expected from any level of emissions calculated in the inventory stage depends in part on the conditions of the local 'receiving environment': eg the existing health of the human population exposed, or the existing quality of a watercourse. These local receiving conditions are not routinely taken into account in midpoint or endpoint assessments undertaken for this sort of LCA. Endpoint impact categories do take into account the differing indoor, outdoor, local and global effects of emissions.

2.5.6 Data and data quality

Table 8 shows the data sources for the main items covered in the three scenarios.

Table 8 Data sources for main items in environmental assessment

Item	Data source
Lithium Iron Phosphate Battery (LFP)	Bespoke model built using base data from Ecoinvent v3.6. Assumed built in China.
PV panel	Existing model in Ecoinvent v3.6. Global averaged data used. NOTE: the data from Ecoinvent assumed the panels were approximately 8% efficient. For all assessments in this paper, the panels were assumed to be 16% efficient (current industry average) but no changes were made to the manufacturing data. This will have caused increased uncertainty around the impacts for PV panel systems.
Inverter/converter	Scaled from 2.5kW existing model in Ecoinvent v3.6. Global averaged data used
Shipping container for Mini-grid (housing)	Bespoke model built using base data from Ecoinvent v3.6. Global averaged data used
Mini-grid Wooden poles and stays	Bespoke models built using base data from Ecoinvent v3.6. Data for wood from 'rest of world' (excludes Europe), global averaged data for preservation process.
Mini-grid Cables and wires	Bespoke models built using base data from Ecoinvent v3.6. Global averaged data used
Mini-grid PVC components	Bespoke models built using base data from Ecoinvent v3.6. Global averaged data used
Mini-grid Overhead equipment	Bespoke model built using base data from Ecoinvent v3.6. Global averaged data used
Simple Electric Pressure Cooker (sEPC)	Teardown for Bill of Material (BoM) and process Ecoinvent v3.6. Global averaged data used
Street Charcoal Burner (sCHB)	BoM estimated from dimensions. Ecoinvent v3.6. Global averaged data used
Liquified Petroleum Gas Burner (LPGB)	Teardown for BoM and process Ecoinvent v3.6. Global averaged data used
Hotplate (HP)	Teardown for BoM and process Ecoinvent v3.6. Global averaged data used
Charcoal production in Kenya	Academic Papers for BoM (Pennise, Singh) and process Ecoinvent v3.6. Global averaged data used
Grid Electricity for Zambia	Ecoinvent v3.6. Grid mix for Zambia (2016) used.
LPG production	Ecoinvent v3.6. Global averaged data used
Fuelwood	Ecoinvent v3.6. Global averaged data used

For much of this analysis, primary data were unavailable or do not exist. Where possible, similar products have been analysed, and appropriate datasets from EcoInvent used to create the required information.

3. Case 1: grid connected cooking in Zambia

3.1 Outline of the case

This first case is set in Zambia, considering households in an urban location who are already connected to the electricity grid, but are not using it for cooking. Three quarters of households in urban areas in Zambia are grid connected (Luzi *et al.*, 2019), with most of the rest having very low level of electricity access. However even amongst the grid connected households the MTF survey of appliance ownership shows that household affluence varies widely with appliance ownership patterns reflective of electricity access tiers 2 to 4 (Luzi et al, 2019 and Energydata.info, 2020). This case envisages a group of some 79 relatively low-income households, connected to a section of distribution network and using a range of appliances for lighting and entertainment, but cooking primarily with charcoal. The opportunities for, and impacts of, some or all of the households transitioning to electric cooking are explored.

Given that this is a grid-connected case, there is no immediate limit on the capacity of the user's connections or of the wider power system to accept additional loads. As such for this case only transition from use of traditional fuels to 100% eCooking is considered. A mixture of Electric Pressure Cookers and hotplates will therefore be used. The power system analysis in section 3.5 will explore the likely outcomes of such a large-scale eCooking transition.

3.2 Assumptions: appliance ownership, demand ratings and usage

3.2.1 Key input assumptions/data

The collection of users connected to the particular section of Low Voltage network is assumed to comprise 79 households. In keeping with the overall context for this case, the households are intended to be urban or peri-urban, with relatively low incomes.

The Zambia MTF country report (Luzi *et al.*, 2019) shows that Urban households are split between Tier 0 and Tier 5 in terms of *capacity* of supply, although this is based simply on the evidence on numbers connected to the grid, and doesn't capture household ownership nor usage of appliances: see Figure 7.

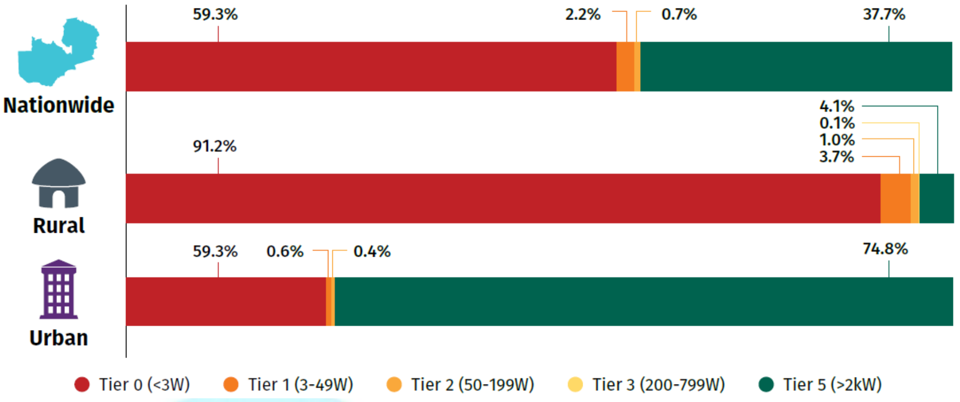

Figure 7 Distribution of households based on electricity capacity in Zambia
Source: Luzi *et al.* (2019)

The report also shows that of those connected in urban areas, around a third experience significant interruptions, and the rest have few. The report itself says little about appliance ownership patterns, as so many urban households are simply classified as being in Tier 5, as they are grid connected and thus have no technical barrier to high power usage. The underpinning survey results database (Energydata.info, 2020) for appliance ownership was analysed and reveals a much more mixed picture. The analysis picked out grid connected, urban households, excluding those who already cook with electricity, reflecting the appliance ownership patterns expected for electricity capacity Tiers 2, 3 or 4.

The case is modelled with two categories of households, broadly consistent with tier 4, but with one (described as tier 4-) having lower level of appliance ownership and use. The appliances attributed to these two household categories are given in Table 9 and Table 10, and draws on the appliance lists in Table 4, primarily from group 1. The case is intended to represent relatively low income urban households, who have a grid connection but are not yet using it for electric cooking, and who don't already own a very wide range of higher power appliances. As such the case does not include those with MTF tier 5 energy access.

Within each of the two household types, 50% of households are assumed to have daytime occupancy, and 50% are assumed to be vacant during the day. This is an arbitrary assumption, but is used to show the significance of occupancy. So there are essentially 4 different household types.

Table 9 Appliances within tier 4- Households, Zambia case

Appliances	**Power Consumption (Watts/appliance)**	**Quantity**	**Hours/day**[6]
Lights	1.2, 1.2, 1.2, 1.2, 2, 2, 2, 2	8	2
Phone Charger	2.5	1	2
Radio	4	1	4
Fan	20	1	6
AC TV	40	1	2
Refrigerator	100	1	24hr cycling
Average daily energy consumption (Wh/day)		855	

Table 10 Appliances within tier 4 Households, Zambia case

Appliances	**Power Consumption (Watts/appliance)**	**Quantity**	**Hours/day**
Lights	1.2, 1.2, 1.2, 1.2, 2, 2, 4, 4, 4, 4	10	2
Phone Charger	2.5	2	2
Radio	4 (1W standby)	1	4
Security Lights	5	1	Overnight
Fan	40	1	6
AC TV	40	1	4
Refrigerator	150	1	24hr cycling
Average daily energy consumption (Wh/day)		1120	

3.2.2 eCooking assumptions

The key data and assumptions used in the MECS household load model's cooking sub-model to represent each element of the household cooking patterns are discussed below. Many estimates are drawn from the Cooking

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[6] The hours/day usage will be lower for households with no or low daytime occupancy, as there are fewer occupied hours in which the probability processes in the model will consider whether to 'start' the appliance.

Diaries study in Zambia (Leary, Scott, Serenje, *et al.*, 2019), which was conducted among a small, non-representative sample of 20 participants based in urban Lusaka.

3.2.2.1 *Number of people cooked for*

The cooking diaries study for Zambia is reported in Jon Leary, Nigel Scott, *et al.* (2019). Further analysis of the data was undertaken to show the number of people cooked for, shown in Table 11. There is evidently little variation between numbers typically present for the three meals, with just some minor reduction at lunch.

Table 11 Meal time occupancy from Zambia cooking diaries

		Adults	Children	TOTAL PERSONS (adults + children)
Breakfast	No. of meals	465	319	471
	Mean	2.862	2.307	4.39
	Std. Deviation	1.6408	1.582	2.792
	25%	2	1	3
	50%	2	2	4
	75%	4	3	5
Lunch	No. of meals	529	332	532
	Mean	2.667	2.172	4.01
	Std. Deviation	1.5772	1.6592	2.684
	25%	2	1	2
	50%	2	1	3
	75%	3	3	5
Dinner	No. of meals	634	428	635
	Mean	2.938	2.565	4.66
	Std. Deviation	1.8965	1.9748	3.429
	25%	2	1	3
	50%	2	2	3
	75%	3	3	6

For the present study, four household types were developed: representing “tier4-“ and “tier4” appliance ownership, and variants representing households for which people are typically present during the day, and where they are not. The pair of tier4- households are further assumed to be larger (comprising more residents) than those of tier 4, to capture another element of diversity. The occupancy means and standard deviations used to represent these cases are shown in Table 12. The assumptions are chosen to be broadly consistent with the cooking diary evidence shown in Table 11, but the specific household details are hypothetical, as this analysis is illustrative of the modelling approach rather than being rooted in a specific place. Each run of the model sets the meal time occupancy for the household type being considered based on a random draw from a normal distribution with the mean and SD shown.

Table 12 Meal time occupancy, Zambia case assumptions

	Case 1a: tier 4-				Case 1b: tier 4			
	Adult Mean	**Adult Standard deviation**	**Children Mean**	**Children Standard deviation**	**Adult Mean**	**Adult Standard deviation**	**Children Mean**	**Children Standard deviation**
Residents	4		3		3		2	
Breakfast	4	1.6	3	1.6	3	1.6	2	1.6
Lunch	3	1.5	3	1.6	2	1.5	2	1.6
Dinner	3	1.9	3	1.9	3	1.9	2	1.9

3.2.2.2 *Meal time periods*

The cooking diaries study for Zambia (Jon Leary, Nigel Scott, *et al.*, 2019) shows the times of day that households start preparing meals, and the durations of preparation. The MECS demand model considers 'starting' each cooking appliance each minute, but only within the specified time periods for each meal type. The start of each period was defined as the 25th percentile of the range of meal preparation start times in Jon Leary, Nigel Scott, *et al.* (2019) table 52. The end of each period was set as the 75th percentile of meal preparation start times plus the median cooking duration for that meal (table 49). The values used are shown in Table 13. The actual start times in any run of the model depend on the probability process that considers whether to start the appliance in each minute in turn. For some runs this will result in no use of the (or potentially any) appliance for a meal.

Table 13 Cooking periods, Zambia

	Cases 1a and 1b	
	Start of period	**End of period**
Breakfast	08:00	09:52
Lunch	11:05	14:17
Dinner	17:50	20:20

3.2.2.3 *Meals cooked with electricity*

During the Zambian cooking diaries study charcoal was the dominant fuel used, with only one household using firewood and LPG not used. After transitioning to cook with electricity, hotplates and EPCs (and/or rice cookers) were used, in some cases stacked with the traditional fuels.

For this grid-connected case, it was assumed that eCooking would potentially be used for all three meals: a 100% eCooking scenario, with no traditional fuel used. The cooking diaries show that people typically take less time preparing breakfast and are more frequently reheating previously cooked food. Thus for the present study breakfasts are assumed to be cooked with just a hotplate, and for lunch and dinner either or both of a hotplate and EPC may be used.

- Breakfast: hotplate only, long use
- Lunch: hotplate, quick use plus EPC, quick use
- Dinner: hotplate, quick use and EPC, long use

The model's probability processes for starting appliances considers each cooking appliance independently and hence affects whether multiple appliances are used sequentially or simultaneously, reflecting realistic variation in kitchen practices.

3.3 MECS household load modelling

The requirement for the grid power system analysis is for a set of 79 households. As such the MECS demand model was run 20 times for each of the two tier 4- household types, 20 times for the tier 4 household with daytime occupancy and 19 times for the tier 4 household with no daytime occupancy.

The model produces values for the electrical power for each of lighting, appliances and cooking, for each minute of the 24 hours, for each run of the model. A model run implements the various probability processes (affecting occupancy, lighting and appliance usage, cooking activity) and thus represents a unique instance of that household type.

Figure 8 shows the aggregate of 79 model runs, used to represent the aggregate load profile of the set of 79 households supplied by the LV network.

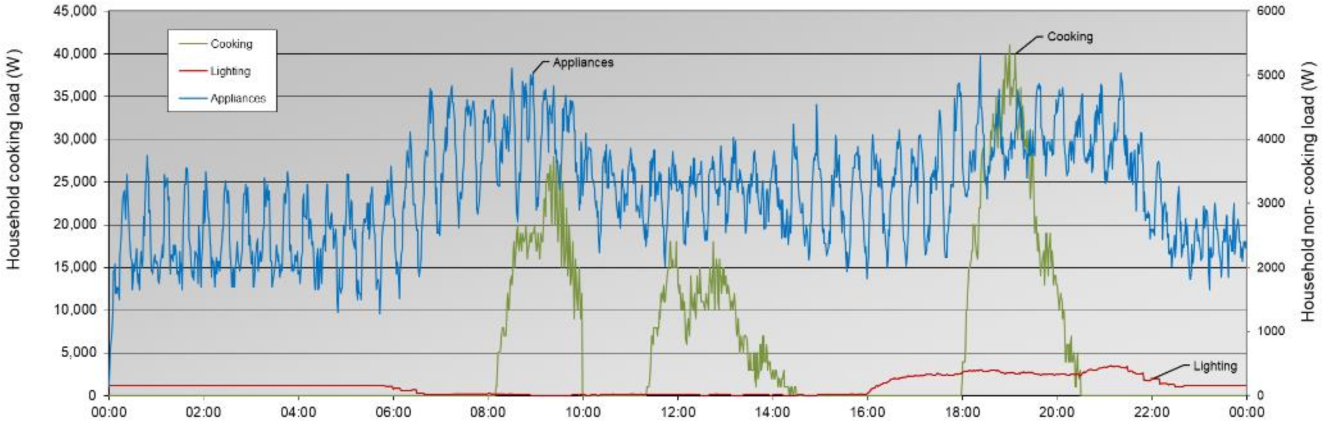

Figure 8 79 household aggregate load profile for 79 households, Zambia

The lighting load is almost zero during daylight hours. Overnight, the tier 4 households are assumed to have a security light in use. Lighting load peaks during the evening, as might be expected. The appliance load has a rapid cycling, caused by the on/off cycles of the refrigerators in each household: the phasing of the individual cycles is random, but with a sample of only 79, some pattern will often be evident. The appliance loads overall are lowest at night, with only refrigerators, security lights and radio standby loads operating. Usage picks up around breakfast time and again in the evening, with lower use during the middle of the day, as 50% of the households are assumed to have no occupancy during the day, and occupancy also reduces with some household members at work or school. The peak of the aggregate appliance load is 5 kW, which equates to a diversified mean of 63 W per household.

The cooking loads are concentrated into the three defined cooking periods. The cooking peak (the ADMD) is 40 kW, occurring while dinner is cooked, which equates to a diversified mean of 500 W per household. Given that the majority of households will be cooking dinner at some point during the 2.5 hour period, and that both hotplate and EPC could be in use, an average of 500 W shows a considerable effect of diversity compared to the maximum peak of 2 kW per household that could be observed. This diversity reflects: variation in timing of hotplate and EPC use, such that they may be sequential rather than overlapping; that some households will only use one appliance; and that some households may be modelled as not cooking dinner at all. This latter possibility reflects the observations in Jon Leary, Nigel Scott, *et al.* (2019) that dinners are not prepared on 20% of days. The overall ADMD for all uses of electricity is 45 kW, equivalent to an average of 570 W per household.

Figure 9 shows the cumulative use of electricity over the day, for cooking and non-cooking (appliance + lighting) uses.

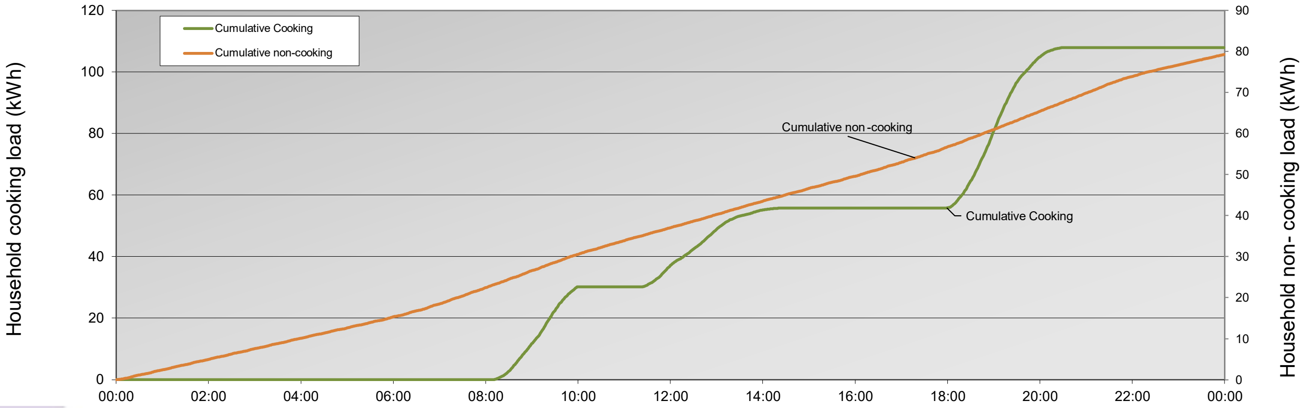

Figure 9 Cumulative load over the day for 79 households, Zambia

While cooking power loads are much higher than non-cooking uses, the aggregate energy uses over the day are quite similar. Figure 10 summarises the shares of energy used for each purpose for the full set of 79 households over the day. While eCooking would increase the peak power load on the network by a factor of 8, it would only increase electricity use by a factor of 2.

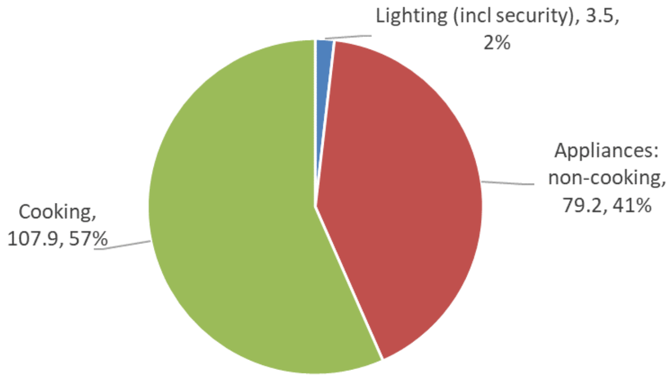

Figure 10 Shares of daily energy use for 79 households, Zambia

Figure 11 shows the load profile for one example tier 4- household. The upper chart has a smaller scale to show the cooking loads and the lower chart is at larger scale so non-cooking loads can be seen. The 100 W refrigerator load is evident, cycling 7 mins on and 17 mins off. The 20 W fan is used through the day and the 40 W TV is use in the morning and evening. Lower power devices and lights are used intermittently.

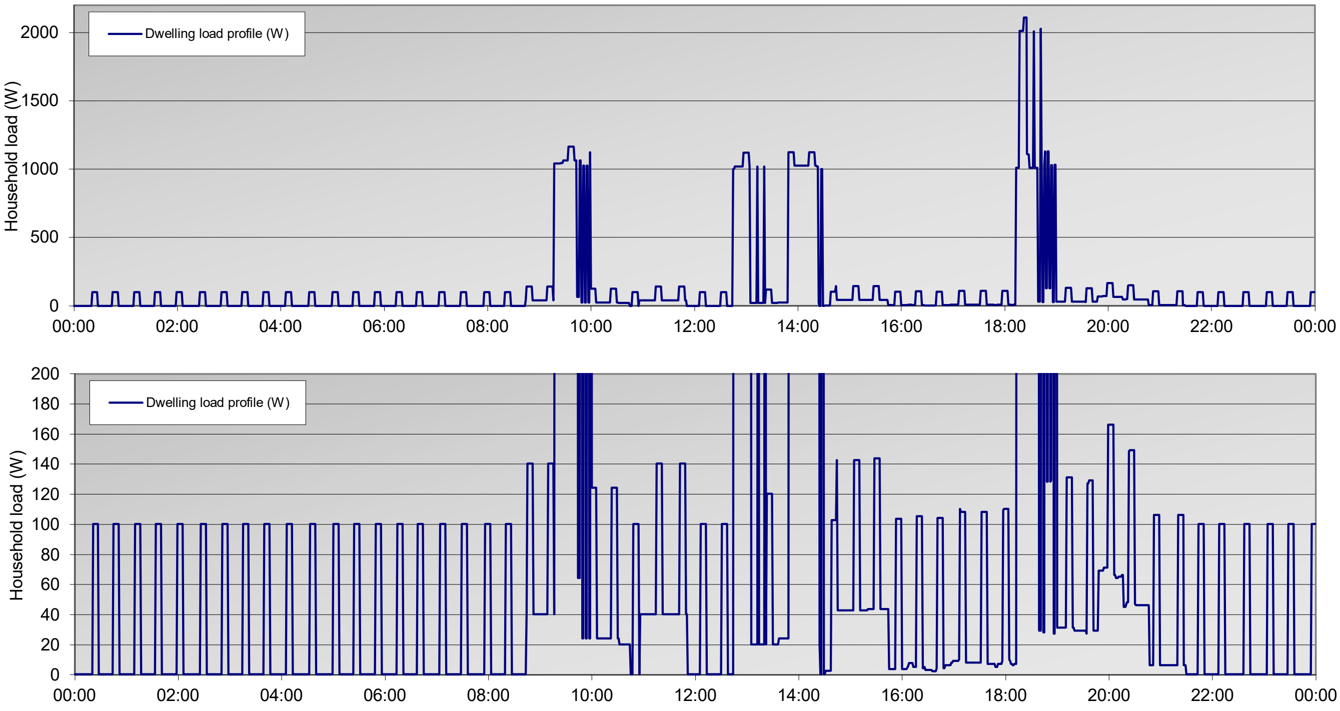

Figure 11 Load profile for one example household, Zambia

Figure 12 shows the dinner period for the same household. The EPC starts first and then the hotplate comes on, leading to a 2 kW cooking load. The sharp spikes represent the EPC moving to its cycling after pre-heat: one minute on at 1 kW and then 7 mins off. On the right the cycling of the hotplate can be seen: 2 mins on and 2 mins off. The cycling of the refrigerator is evident throughout. Some lights and other appliances come on and off, but are too low power to be evident with this chart scale.

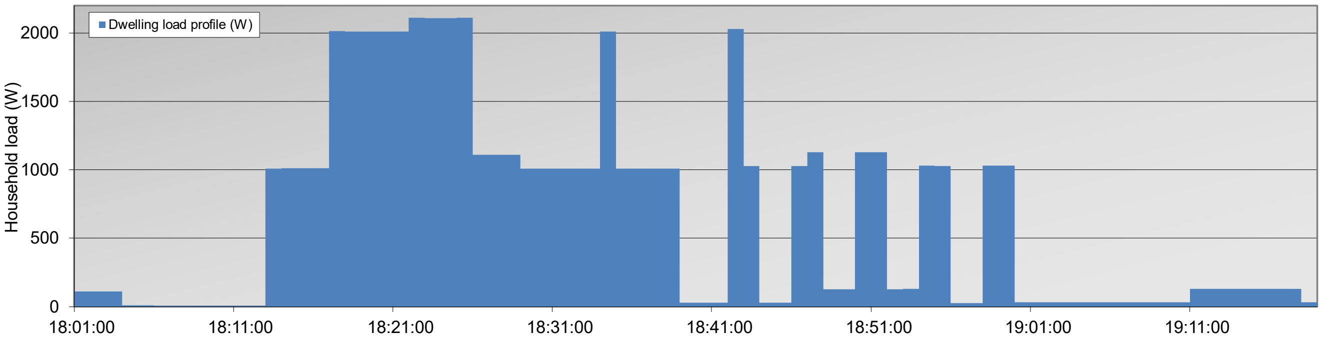

Figure 12 Dinner time for example household, Zambia

3.4 eCook system design and costs

This case for grid connected households in urban Zambia equates to case study 2 in ESMAP (2020) focused on a scenario of 100% replacement of traditional fuels with eCooking, and without battery support. Technically the 'eCook system' in this case is very simple: purchase of regular AC hotplates and EPCs, and their connection to normal household power sockets.

Figure 13 reproduces one of the results charts from ESMAP (2020). The results for this case are circled in red: 100% AC cooking using energy efficient appliances, compared with use of charcoal. Whilst LPG use was not observed in the original cooking diaries study, it is modelled as an option here too.

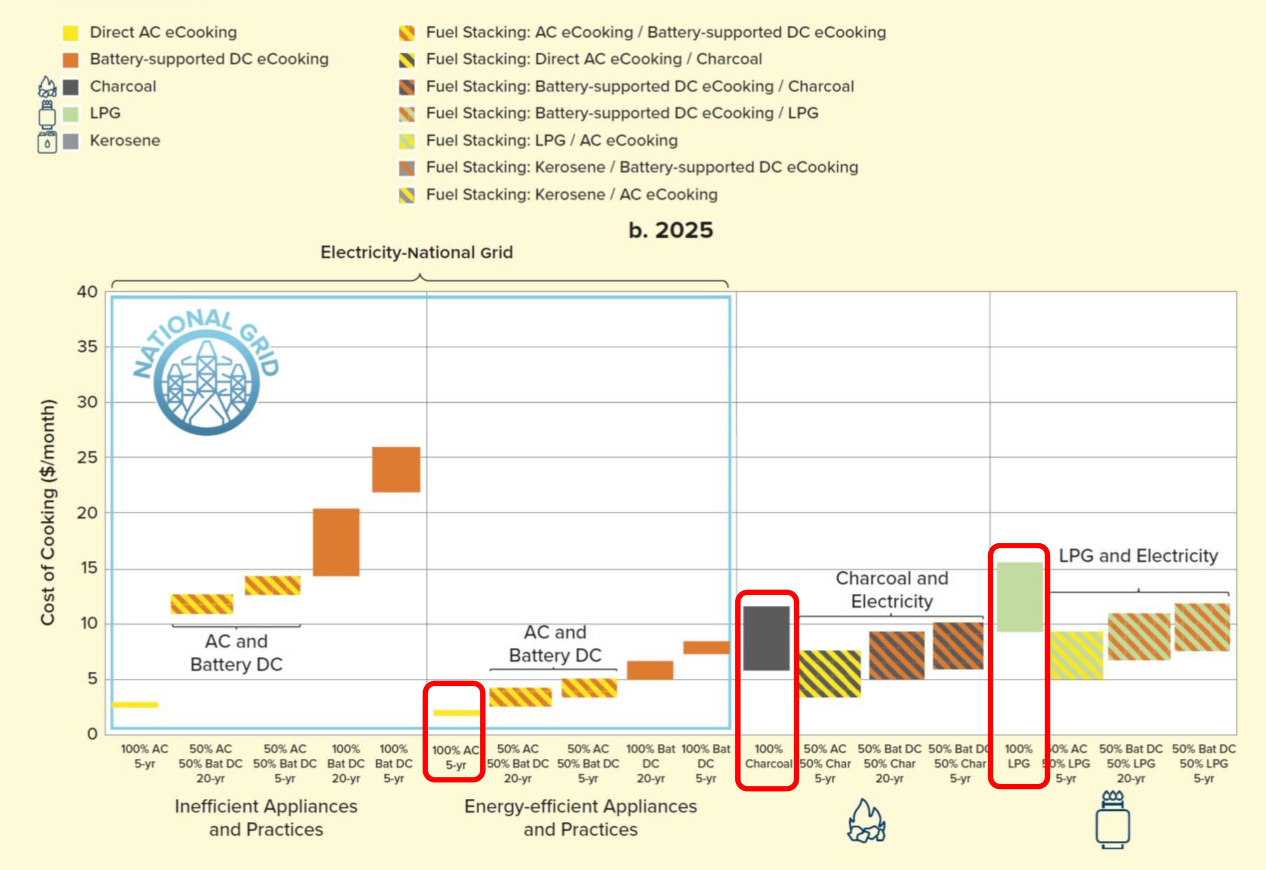

Figure 13 Zambia case study results from ESMAP (2020)

In Zambia the electricity tariffs are low, with a lifeline tariff for the first 200 kWh used per month costing only $0.014/kWh. The MECS demand model shows that the average electricity use for non-cooking services is 1 kWh per day and eCooking adds 1.4 kWh per day, so the total use per month is below 100 kWh per month. eCooking thus costs around $2 per month, compared with $6-12 for charcoal. This is only feasible (without battery support) where the grid is reliable enough to sustain cooking.

3.5 Impact on existing electrical infrastructure

The following analysis presents the impact of electric cooking on available LV network infrastructure that has been parametrised with a Zambian application in mind. A stylised representation of example of the LV network is shown in Figure 14.

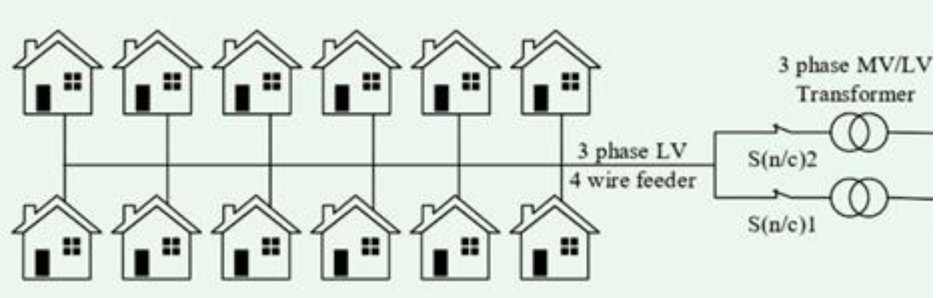

Figure 14 Example of a LV Distribution Network Arrangement

The LV network used for analysis is energised through a distribution substation which steps down the voltage to 230 V (single-phase) and 400 V (three-phase) at 50 Hz which is typical for LV system configuration in Zambia. Operationally, the rating of the transformer is selected based on estimated power consumption within houses connected to the same substation. Initial investigations suggest that many LV networks in Zambia are oversized at the planning stage to allow for moderate demand growth over the next 15-20 years (Government of the Republic of Zambia, 2009). The selection of transformer capacity depends on the total After Diversity Maximum Demand (ADMD) parameter[7] - which can vary depending on types of electricity consumers, connected downstream from the substation – and is also reflective the network planners view of growth. Based on previous studies that give an understanding of LV distribution network design in Zambia, the ADMD per domestic household is set to 500 W.

The geographical sizing of the distribution network is another aspect considered in the research. This will have a crucial impact on analysis of the voltage profiles at different stages of the system, especially after the connection of cooking appliances which may require high power to be delivered for sustained periods and/or over long distances. As a result, the maximum voltage drop allowed by the network providers could be exceeded in such cases, meaning that the overall power distribution efficiency can be low.

To represent a generalised model of the LV distribution system, Aerial-Bundle Cable (ABC) with a cross-sectional area of 50 mm^2 was selected as this is typically used for LV network design in various countries across sub-Saharan Africa. Occasionally, in areas of low power consumption and relatively short distances from the substation, 35 mm^2 ABC can be used to reduce system expenditure costs.

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[7] See http://www.networkrevolution.co.uk/project-library/diversity-maximum-demand-admd-report/

As discussed in section 2.4, the LV network model configuration is based on systems in Malawi. To estimate the number of households connected downstream from a secondary transformer, the populations as well as the number and rating of transformers installed in a set of five different villages were studied. It was found that a single substation provides electricity to a minimum of 21 and maximum of 111 households. The recommended distance from the substation, however, should be less than 500 metres.

With these network parameters in place a series of power flow studies were conducted on a network model which represents typical LV networks in Zambia. The results indicate that LV networks can already serve a high penetration of electric cooking loads. Figure 15 shows an aggregated daily demand profile on the LV network after adoption of eCook at each of the 79 households considered. This figure is very similar in shape to the modelled household loads of Figure 8, which are input data for the network modelling. However Figure 15 includes the influence of the assumed spatial distribution of households and the attendant distribution losses. Here it is clear that the 50 kVA limit on the substation transformer has not been breached in this case and furthermore, this is true for other sensitivity studies considered on Zambian LV networks (e.g. relocating the generating source). While these cases are not reported on here, they confirm that reaching high penetrations of eCook devices is possible. This is mainly due to network assets being over-rated compared to typical load conditions and in this sense the network is 'overdesigned'.

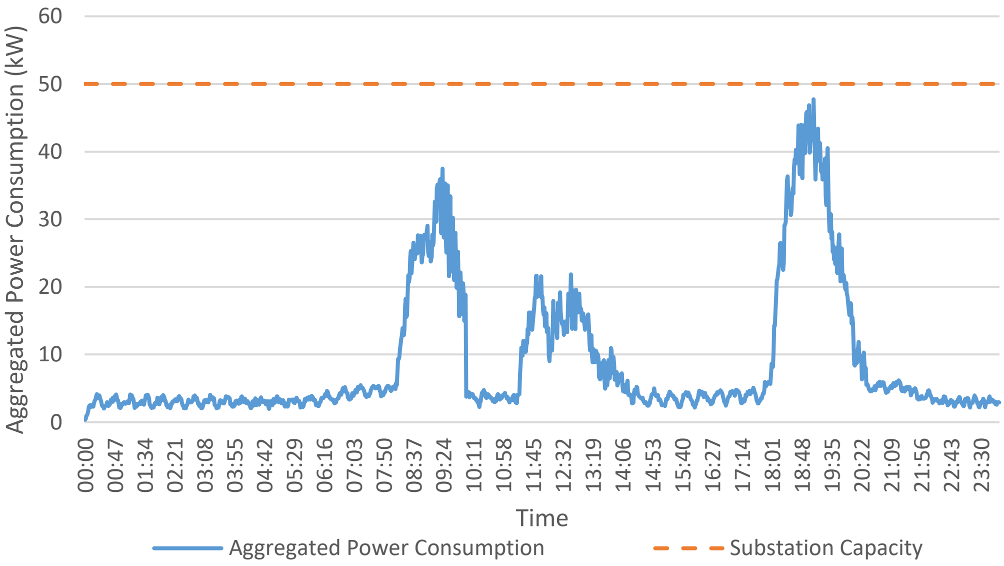

Figure 15 Estimated Demand after Connecting eCook Appliances with Zambian LV Network

Low load factors within LV networks deployed in Zambia show great potential for adoption of electric cooking devices. Although capacity installed below the secondary substation is high enough to reach very significant eCook penetrations, further studies are recommended in order to analyse impact of eCook on MV distribution and HV transmission to verify whereas these stages of the power system are robust enough, similar to LV networks. Other potential aspects to be verified are associated with the overall grid reliability associated with generation shortages to meet fast growing electric demand (approximately 3.5% per year) (Owen, 2016).

Figure 15 indicates that the maximum demand supplied by the 11/0.4 kV substation while providing eCook appliance to all 79 households is approximately 48 kVA. It implies that the ADMD per household is 604 VA[8]. This

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[8] This calculated by dividing maximum demand over number of households

parameter was therefore used to present voltage distribution within LV network while being exposed to 604 VA load at each of 79 households connected to the network. The results are presented in Figure 16 where 1 p.u. is equivalent to 400 V/230 V.

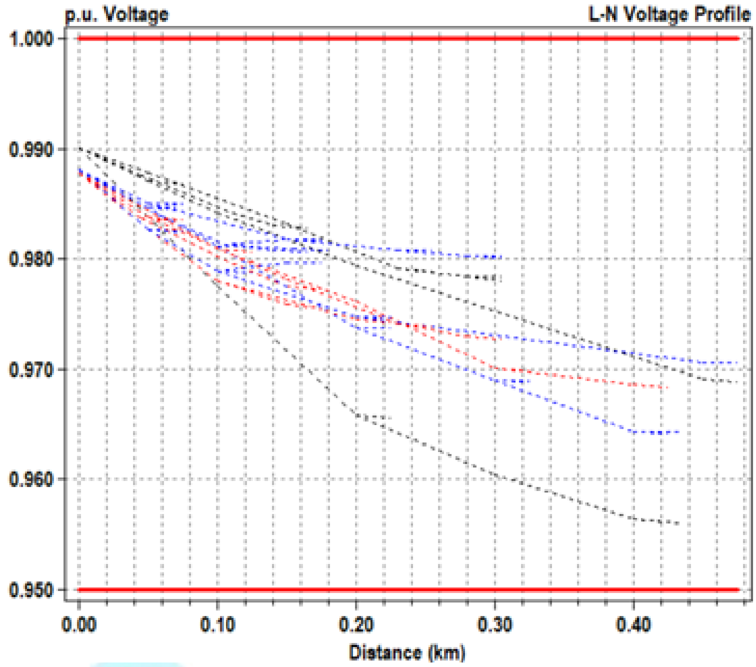


Figure 16 Voltage Profiles within LV network after introduction of 1 kW EPCs

Looking at the cabling specifically, studies revealed that 50 mm^2 ABC cables (those typically installed within LV and mini-grid networks in sub-Saharan Africa (SSA)) can support 100% of households using 1 kW Electric Pressure Cookers (EPCs) and hotplates. Distribution network thermal limits are not expected to be exceeded. Furthermore, the maximum voltage drop while serving peak demand for those networks consider, should not exceed 5% of the nominal as recommended in the network standards in SSA .

3.6 Environmental impact

Figure 17 shows the system diagram for case study 1, comparing cooking with grid electricity and charcoal in Zambia. Although LPG is not widely used in Lusaka because it is expensive and regarded as unsafe, it does provide a modern energy alternative, so LPG based cooking has also been explored. All the options modelled for Zambia are given in Table 14.

Table 14 Options assessed for Zambia

Scenario	Devices	Quantities/per household per day
100% Charcoal	Ceramic Jiko	1.67 kg charcoal
100% LPG	2 Ring LPG burner	0.27 kg LPG
100% Grid	sEPC Hotplate	1.40 kWh

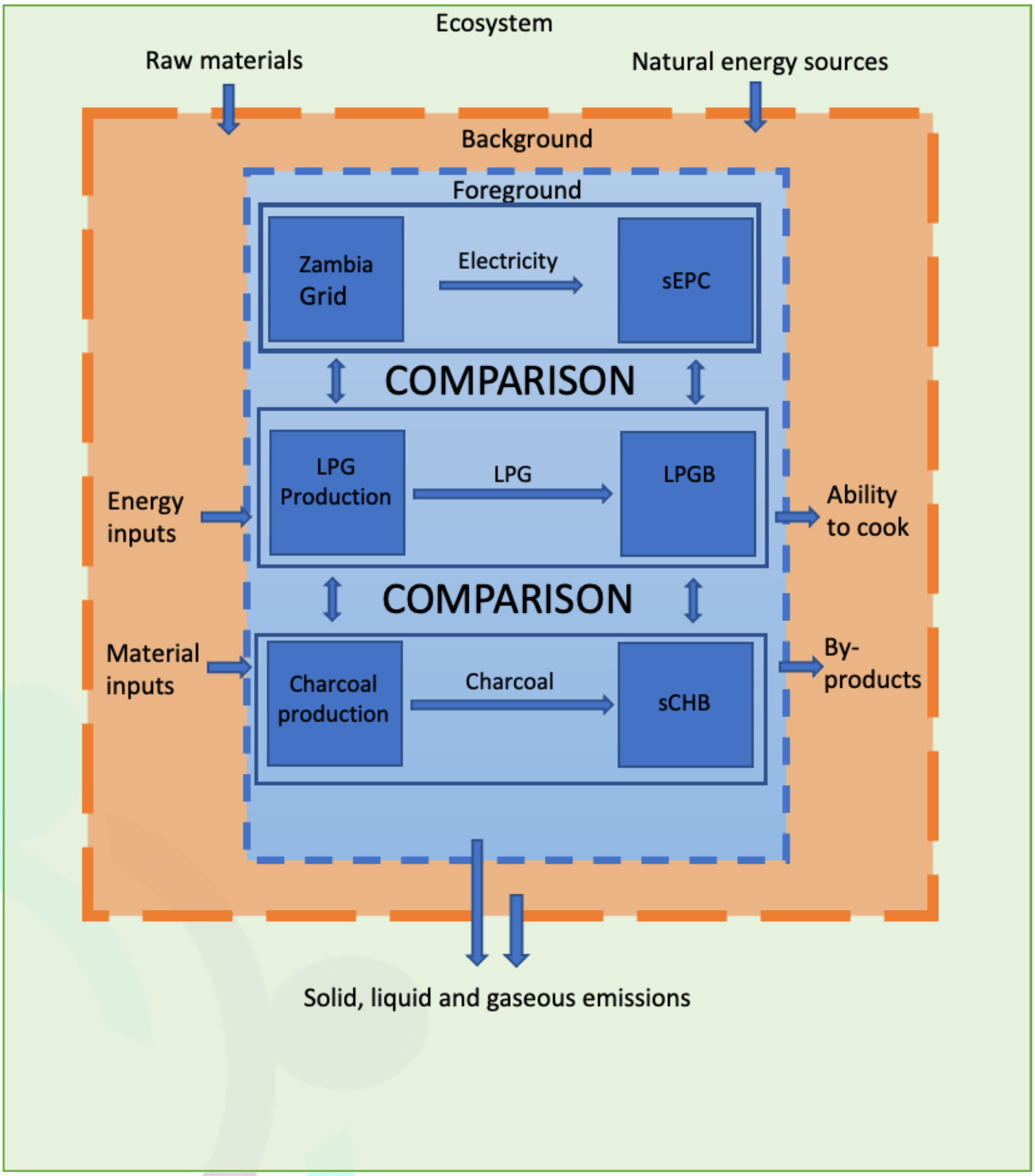


Figure 17 System diagram for Environmental assessment of Zambia case

The fuel use quantities are scaled up from the original data in Table 6, as those are normalised for a 4.2 person household. The household sizes modelled in this case are somewhat larger, as seen in Table 12.

The midpoint indicator results (Figure 18 and Figure 19) show very clearly that the charcoal stoves exhibit the highest environmental impact potential across all environmental categories. An interesting outlier is that of the potential human carcinogenic impact from the use of LPG. This is significantly higher than any other potential impact for LPG, and is caused by the use of chromium plating on the LPG stove and on equipment used within the manufacture of LPG. Figure 19 shows the normalised results, against global average per capita impact (showing the ratio of the impact category under review to the global average per capita impact category), it can be seen that the toxicity impact categories, (human, marine and freshwater toxicity) dominate.

The results show that charcoal use from the system under review emits the equivalent of 14% of the global average per capita emissions for marine ecotoxicity, i.e. it has a proportionally big effect. This result appears to make little sense, as the connection between charcoal and marine environments is not obvious. However, toxicity is measured via the exposure and transmission of the reference unit 1,4 dichlorobenzene equivalent, and comes from many sources. In the case of charcoal, the main sources are zinc, from the waste processing of vehicles, and the management of sulphidic tailings from copper production. This suggests that the high impact of marine toxicity is as a result of background processes and systems supporting, rather than the foreground systems most easily connected to, charcoal production and use.

Digging into the causes of the environmental impact results for climate change, particulate production and human toxicity - the most relevant impact categories for MECS - the following causes are found:

For climate change:

- In the grid scenario, the impact is caused by the use of coal in electricity production despite the fact that in Zambia coal contributes only 2% of the grid mix, the main power source being hydroelectricity (80%).
- For LPG, the impact is caused by the combustion of the LPG, in the home.
- For Charcoal, the impact results from the manufacture of charcoal in earth kilns, where emissions are to open air, and its combustion in the home. Incomplete combustion as a result of the reducing atmosphere needed to produce charcoal, creates emissions that lead to the greatest climate change concern.

For particulate emissions:

- In the grid scenario, the impact is again caused by the use of coal in electricity production.
- For LPG, the impact arises from the production of LPG and the process of gas flaring.
- For Charcoal, the impact is caused by forest management processes (it is assumed in the charcoal production process that 50% of wood for charcoal production comes from managed forests, and 50% is simply 'collected'), and charcoal combustion in the home. The forest management process requires machinery and fuel to support the growing and harvesting of wood.

For carcinogenic human toxicity

- In the grid scenario, two factors contribute most, the spoil from coal mining, and the construction of the distribution network.
- For LPG, as mentioned earlier, the use of chromium plated steel is the root cause.
- For Charcoal, the main cause is the residue/slag from steel production furnaces that are disposed of to landfill. The steel in the system comes not directly from the earth mound kiln production, but from steel in the vehicles used in forest management and transport of charcoal to market. The impact of this steel far outweighs the impact of steel used in the production of the cooking devices themselves.

For non-carcinogenic human toxicity

- In the grid scenario, the ash from coal combustion and spoil form coal and lignite mining are the key contributors.
- For LPG, spoil from coal and lignite mining, used to produce electricity that is used in the production of LPG, is the main contributing factor. Here it should be remembered that LPG is produced in a global market, and the electricity mixes for locations where LPG is produced will vary significantly and can contain high percentages of fossil-based fuels.
- For charcoal, the greatest contributor is zinc, found in the residue from vehicle shredding. The most likely cause is the background systems associated with the production of charcoal.

To understand the impact on human health, ecosystems and resource use, the midpoint environmental category results are assigned to the three endpoint indicators. These graphs allow for easier comparison between the cooking options, but can also hide subtle issues. Figure 20 shows the relative damage to each of the endpoint indicators from the cooking options. As to be expected, charcoal use with a simple charcoal burner creates the highest impacts on health, eco-systems and resource use. Cooking on the grid has the lowest impact for all three endpoints. The high score for resources for LPG is a result of petroleum production.

Combining all the endpoint impacts into a single score gives an indication of which cooking method has the least environmental impact. From Figure 21, it can be seen that grid cooking is the preferred method, closely followed by LPG, whilst charcoal cooking with a street charcoal burner is significantly worse. As expected from the normalised midpoint impact category results, for each cooking option, the impact to human health outweighs the impact to ecosystems and resource use. It should be noted here that the results for the grid assume steady state, e.g. that the infrastructure is already in place, and that no new generating capacity is needed to meet the increased demand. Clearly, for small remote rural communities, the infrastructure requirements for connection could be substantial. Initial studies into the environmental impact of infrastructure needs for a mini-grid suggest that poles and cabling requirements are not insignificant, thus it is reasonable to assume that the additional infrastructure needs of expanding the grid should be evaluated for each potential location, as they may result in a significantly higher impact than the production and use of LPG. For urban environments, this is not likely to be the case.

A sensitivity analysis of grid composition was undertaken to understand the effect of different electricity sources on environmental impact. Zambia currently produces at least 80% of its power from hydro, so it has limited opportunity for increasing this proportion significantly. Figure 22 show the effect on grid cooking impact, against other cooking options. It can be seen that a modest increase in hydro of 5% to a total of 85% hydro, (and reducing national grid production from oil and coal to zero) reduces the impact of grid cooking to a level approximately one third that for LPG. Conversely, a reduction in hydro power to 40% and corresponding increase in fossil derived electricity (44%) shows an impact only just higher than that from LPG. This suggests that there is some room for expansion of the grid, not necessarily from renewable resources, that can be accommodated, without significantly increasing the environmental impact.

3.6.1 Summary of environmental impacts

The results show that a switch away from charcoal would deliver an improved environmental outcome. LPG and grid cooking are relatively close in impact in comparison to the impacts from charcoal based cooking, and neither of these production chains are under the direct control of the users. Therefore, detailed investigation into the production routes of these are required in order to provide guidance for future clean cooking options in order to assess:

- Under what conditions could the grid be expanded geographically, or in capacity, to allow more households to connect?
- What would be the impact if that extra capacity were fuelled from fossil based reserves, or imported from countries that generate their power predominantly from fossil resources?
- There are emerging opportunities to create LPG from biomass and this bioLPG would change the impact of LPG for cooking. What are the local opportunities for bioLPG production, including biogas production from organic wastes and/or local agricultural waste?

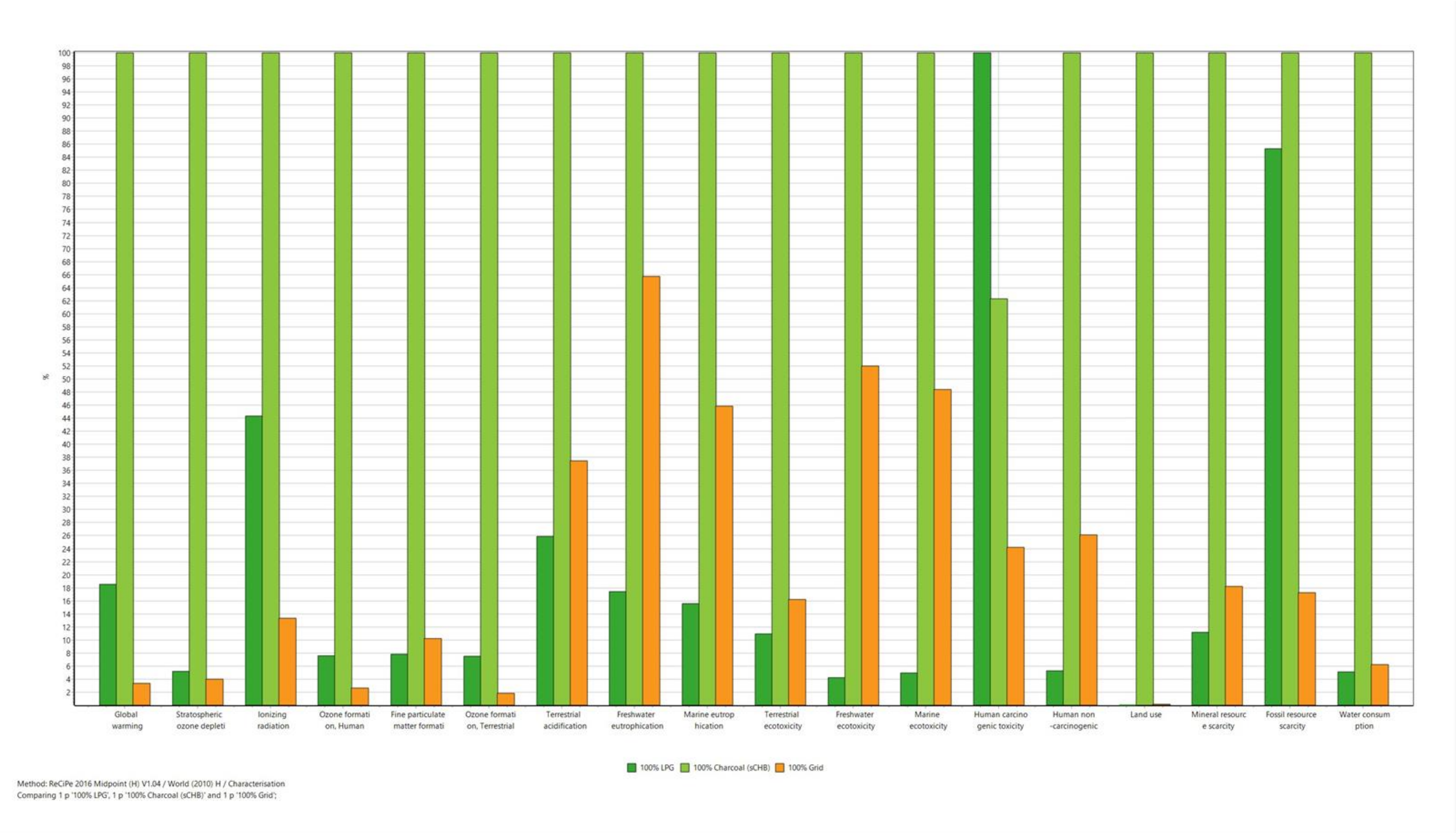
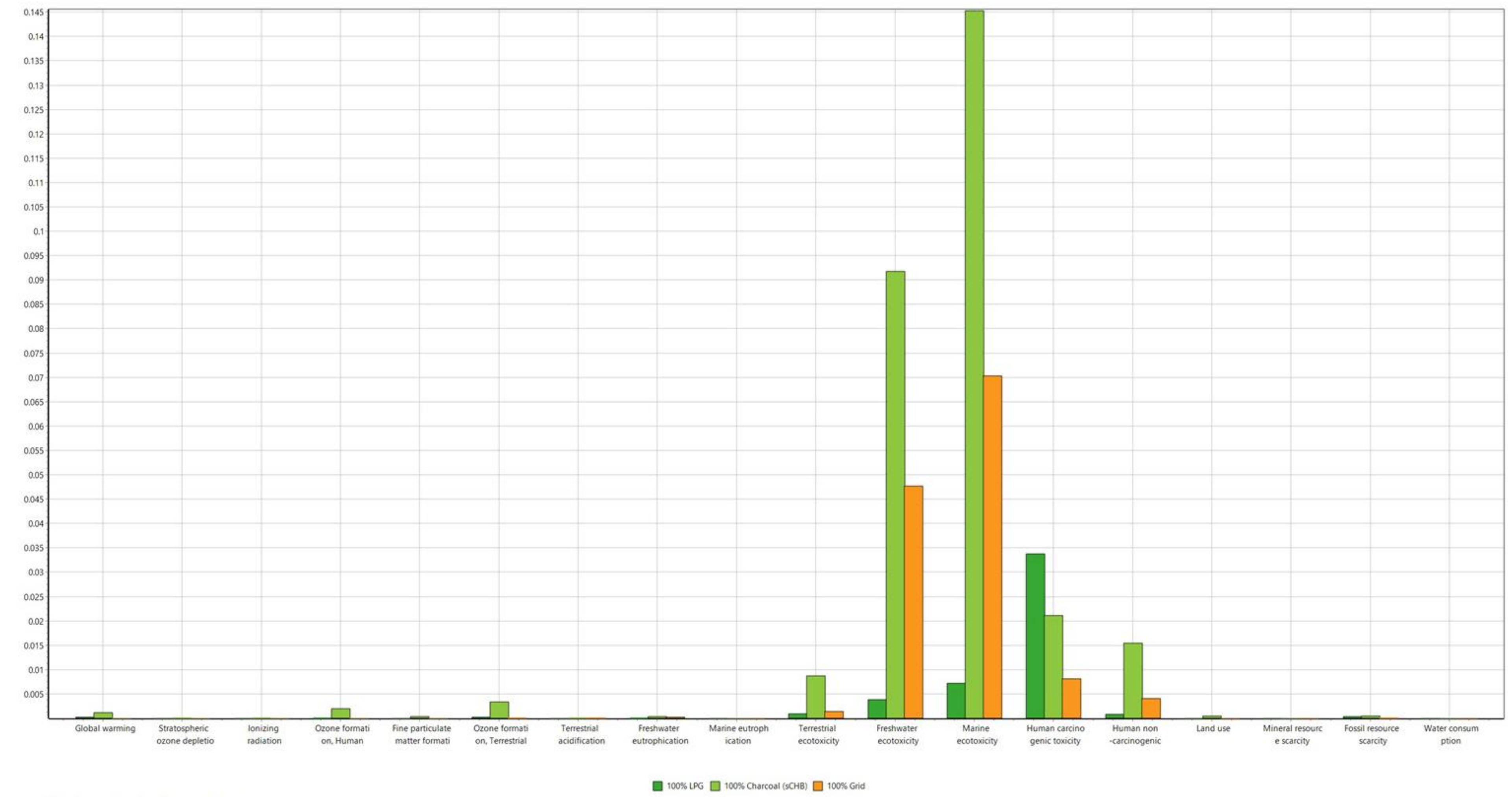


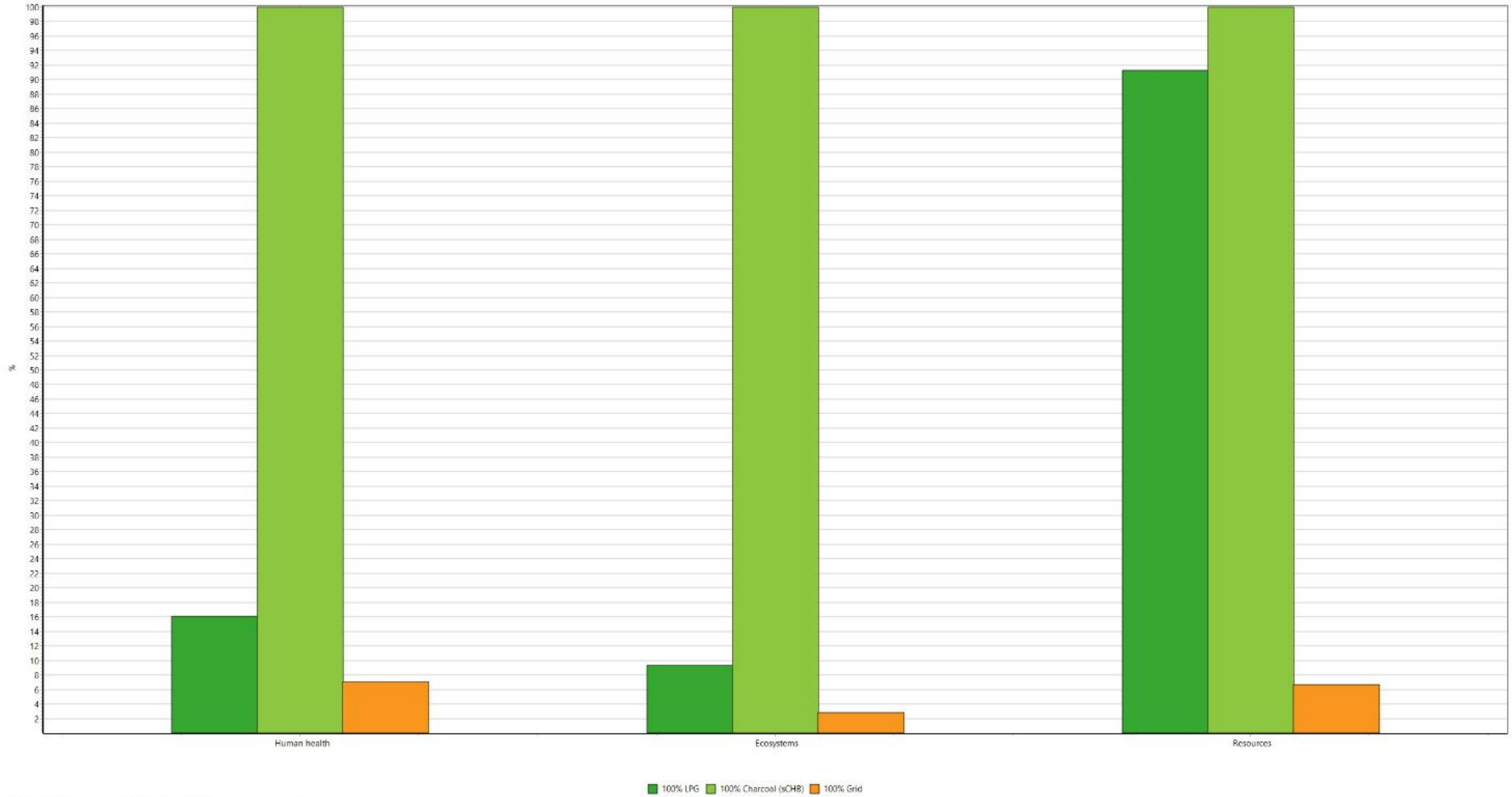
Figure 18 Midpoint Characterisation for Zambia case

(Within each impact category, the option with the highest impact is set to 100% and the impact of each other option is scaled to that).



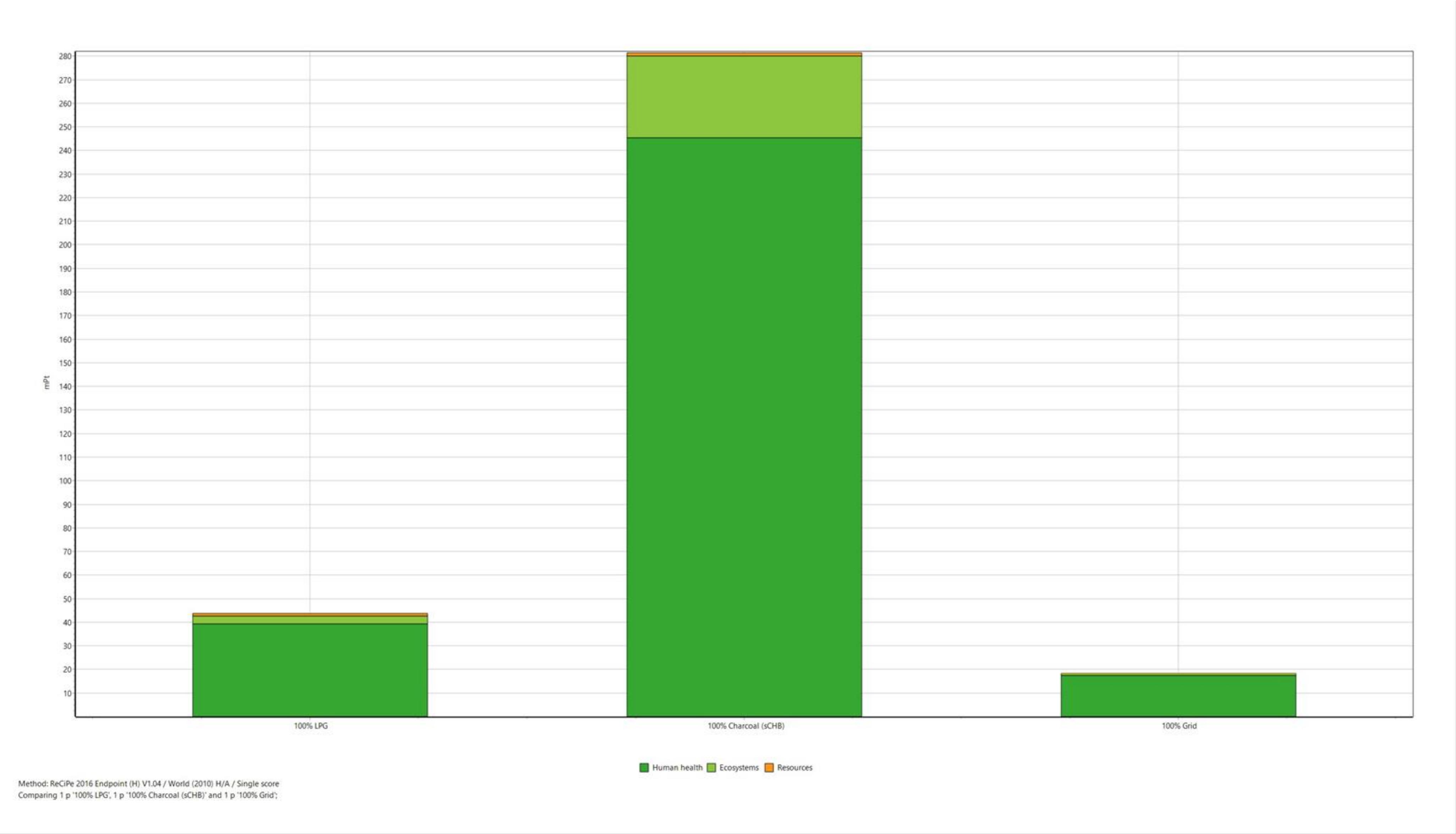
Method: ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H / Normalisation
Comparing 1 p '100% LPG', 1 p '100% Charcoal (sCHB)' and 1 p '100% Grid';

Figure 19 Normalised midpoint impact results for Zambia case
(See section 2.5.5 for explanation of the Eco-indicator point measurement shown here



Method: ReCiPe 2016 Endpoint (H) V1.04 / World (2010) H/A / Damage assessment
Comparing 1 p '100% LPG', 1 p '100% Charcoal (sCHB)' and 1 p '100% Grid';

Figure 20 Damage to endpoint indicators for Zambia case



Method: ReCiPe 2016 Endpoint (H) V1.04 / World (2010) H/A / Single score
Comparing 1 p '100% LPG', 1 p '100% Charcoal (sCHB)' and 1 p '100% Grid';

Figure 21 Endpoint Single score for Zambia case

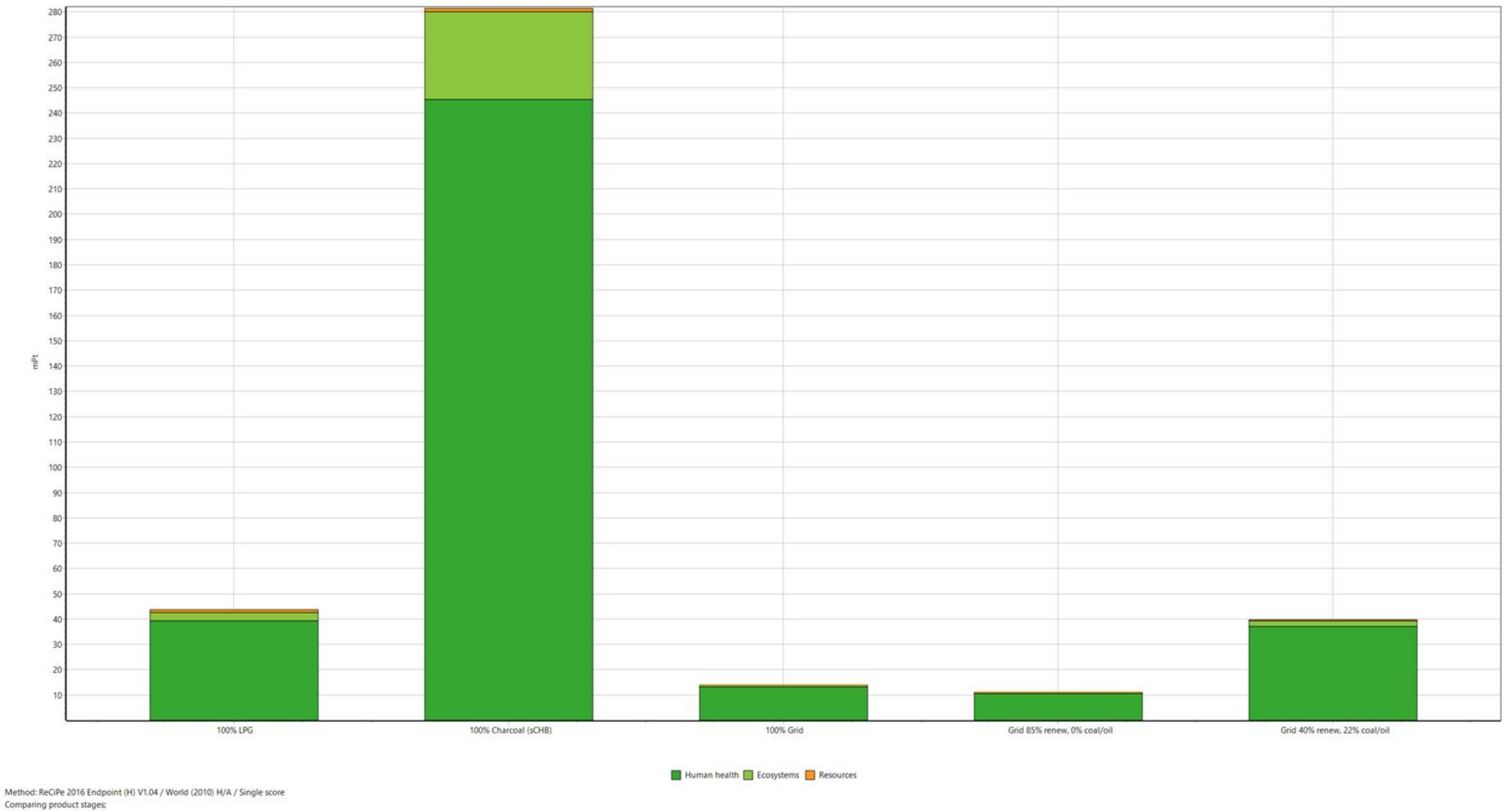


Figure 22 Endpoint single scores for Zambia showing different grid mixes

3.7 Case 1: summary findings

This first case is set in Zambia, considering relatively poor households in an urban location who are already connected to the electricity grid, but are not using it for cooking. Transition from use of traditional fuels to 100% eCooking with a mixture of Electric Pressure Cookers and hotplates is explored.

The findings from application of the demand, eCook, LCA and network models show that:

- Households are using several lights, phone chargers, medium sized radios and TVs, fans and small refrigerators; these appliances total to an installed capacity of around 200 W. However, after diversity effects in the timing of appliance use and household occupancy, the expected peak in daily load from the group is 5 kW, equating to just 63 W per household. Non-cooking electricity use average to around 1 kWh electricity use per household per day.
- A transition to eCooking with a total of 2 kW of cooking appliances per household, after diversity effects in the choices of meals and occupancy, would more than double the total electricity use per day for the group of 79 households. The aggregate (diversified) peak power from cooking will increase the load drawn from the grid by a factor of eight, to 40 kW, equivalent to an average of around 500 W per household.
- The power network analysis for this case showed that the 50 kVA limit on the substation transformer was not breached, distribution network thermal limits are not expected to be exceeded and the maximum voltage drop while serving peak demand should not exceed 5% of the nominal, as recommended in the network standards in SSA. Overall this confirms that high penetrations of eCook devices are possible, mainly due to network assets being over-rated compared to typical load conditions and in this sense the existing network is 'overdesigned'.
- With low electricity tariffs, eCooking in Zambia competes well with charcoal and LPG. The eCook results suggest that with the purchase costs of the cooking appliances spread out, average monthly bills would fall from around $8 per month of spend buying charcoal or $12 per month for LPG, to just $2 per month. This analysis assumes that the grid is reliable enough for eCooking, and as such does not factor in the costs of a household battery.
- The LCA results show that a switch away from charcoal would deliver improved environmental outcomes, with substantial improvements in every impact category. LPG and grid eCooking are relatively low in impact in comparison to charcoal. Impacts to human health outweigh those to ecosystems and resource use, with the key health impacts for each cooking type occurring at different stages in their respective supply chains.

In conclusion, low load factors within LV networks deployed in Zambia, and low tariffs for electricity lead to great potential for adoption of electric cooking devices. Where these are substituting for charcoal, significant reductions in health, ecosystem and resource impacts would result, alongside considerable financial savings for households.

4. Case 2: mini-grid connected cooking in Tanzania

4.1 Outline of the case

The second case study explores the potential for households connected to a solar-diesel hybrid mini-grid in rural or peri-urban Tanzania to transition to electric cooking. The characteristics of the households are similar to those connected to a set of mini-grids owned by Powergen, for which a detailed load monitoring study has been underway (Schreiber, 2020). The case considers a group of 88 households, with appliance ownership representative of electricity access tiers 1 and 2, providing basic lighting and entertainment services. The households cook primarily with charcoal. From an initial assessment of the capacity of the mini-grid it was evident that there would be limits on the number of eCook devices that could be supported. As such this case focuses on a transition to partial eCooking, assuming that EPCs are adopted to cook longer/heavier dishes, stacked with continued but reduced use of traditional fuels. The case therefore explores opportunities for, and impacts of, some of the households transitioning to electric cooking using electric pressure cookers.

4.2 Assumptions: appliance ownership, demand ratings and usage

4.2.1 Key input assumptions/data

The collection of users connected to the mini-grid is assumed to comprise 88 households: this number was chosen to match the set up of the mini-grid network models discussed in section 4.5, which are also aligned to the Powergen mini-grids.

Appliance ownership and utilisation assumptions broadly follow the Multi-Tier Framework definitions. For this case we assume households are a mix of Tier 1 (44HHs) and Tier 2 (44HHs), with the details in Table 15 and Table 16. Since there is no MTF country report for Tanzania, these tiers were selected to match the statistics for tier composition of off-grid households taken from the Kenya MTF country report as per Figure 23. They also align with data from a survey of appliances owned by a sample of households taking part in the Powergen mini-grid load monitoring study in Tanzania (Schreiber, 2020), which gives confidence that using Kenya MTF data is a reasonable assumption. The appliance survey data arise from ongoing activities in the MECS programme and are as yet unpublished, but were used for validation here.

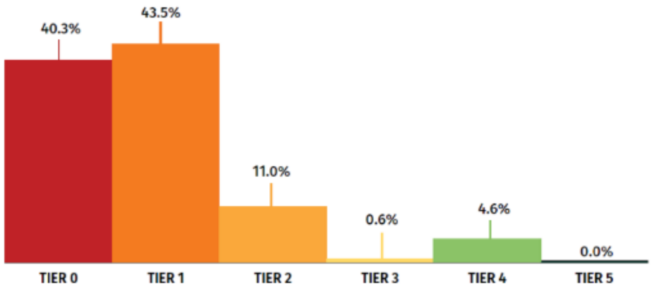


Figure 23 MTF capacity tier distribution for off-grid solar connections in Kenya

For this case, Tier 0 and Tier 4 were not included as Tier 0 equates to “no access” and Tier 4 capacity couldn’t be supported on most mini-grids.

Appliance ownership was adjusted a little from the MTF data, notably to add TV to the Tier 1. The changes were made to better reflect the Powergen appliance survey results, in which most households reported owning a small TV whilst other appliance ownership patterns matched the MTF data well. The households were also all equipped with a controller/interface to the mini-grid, with a baseload power use (William Coley 2020, personal communication).

Within each tier group, 50% of households are assumed to have daytime occupancy, and 50% are assumed to be vacant during the day. This is an arbitrary assumption, but used to match evidence from the Powergen household load study that there is no daytime electricity use in a proportion of households. So, as also seen for the Zambia case in section 3.2.1, there are essentially 4 different household types.

The actual use of appliances and lights is modelled using a variety of probabilistic processes, so the load profile for non-cooking is different for every household. The hours/day shown in the table comes from the MTF report, and is used in the present modelling as an average around which usage by any one household will vary.

Table 15. Appliances within Tier 1 Households, Tanzania case

Appliances	Power Consumption (Watts/appliance)	Quantity	Hours/day
Lights	1.2 each	2	
Phone Charger	2.5	1	2
Radio	2	1	2
TV	20	1	1.5
Grid controller	0.3	1	24hours
Average daily energy consumption (Wh/day)		64	

Table 16. Appliances within Tier 2 Households, Tanzania case

Appliances	Power Consumption (Watts/appliance)	Quantity	Hours/day
Lights	1.2, 1.2, 2, 4, 4	5	
Phone Charger	2.5	2	2
Radio	4 (1 W standby)	1	4
Security Lights	5	1	Overnight
Fan	20	1	4
TV	20	1	2
Grid controller	0.3	1	24hours
Average daily energy consumption (Wh/day)		234	

The higher tier households have a wider range of appliances, but some of these also use more electricity than the equivalent appliances in tier 1 households, reflecting an assumption that the appliances owned have more features or are more powerful.

4.2.2 eCook assumptions

The key data and assumptions used to model each element of the household cooking patterns are discussed below.

4.2.2.1 Number of people cooked for

The cooking diaries study for Tanzania is reported in Jon Leary, N Scott, *et al.* (2019). This was conducted among a small, non-representative sample of 22 participants based in urban Dar es Salaam. Note that this is different to the rural and peri-urban contexts where mingrids are mostly installed. Further analysis of the data was undertaken to show the number of people cooked for, shown in Table 17.

Table 17 Meal time occupancy from Tanzania cooking diaries

		Adults	Children	TOTAL PERSONS (adults + children)
Breakfast	n	834	476	834
	Mean	3.63	1.7	4.6
	Std. Deviation	1.575	0.818	1.862
	25%	3	1	3
	50%	3	1	4
	75%	4	2	6
Lunch	n	752	440	770
	Mean	3.7	1.58	4.52
	Std. Deviation	2.058	0.774	2.321
	25%	2	1	3
	50%	4	1	4
	75%	5	2	6
Dinner	n	788	409	791
	Mean	4.15	1.66	4.99
	Std. Deviation	1.878	0.793	2.195
	25%	3	1	4
	50%	4	1	5
	75%	6	2	6

There is some variation between the number of people cooked for across the three meals, with fewer adults and children cooked for at breakfast and lunch. The two household types developed are chosen to illustrate a larger household and an average sized one. The mean and standard deviation used for the modelling are shown in Table 18. Compared to case 1 for Zambia, the Tanzania households have fewer children, but there is less variability in the numbers of children present for meals, as reflected by lower SDs here. Each run of the model sets the meal time occupancy based on a random draw from a normal distribution with the means and SDs shown.

Table 18 Meal time occupancy, Tanzania case assumptions

	Case 2a: tier 1				Case 2b: tier 2			
	Adult Mean	**Adult Standard deviation**	**Children Mean**	**Children Standard deviation**	**Adult Mean**	**Adult Standard deviation**	**Children Mean**	**Children Standard deviation**
Residents	4		2		3		1	
Breakfast	3	1.6	1	0.82	3	1.6	1	0.82
Lunch	4	2.6	1	0.77	2	2.6	1	0.77
Dinner	4	1.9	2	0.79	3	1.9	1	0.79

4.2.2.2 *Meal time periods*

The cooking diaries study for Tanzania (Leary, N Scott, *et al.*, 2019) shows the times of day that households start preparing meals, and the durations of preparation. The MECS demand model considers 'starting' each cooking appliance each minute, but only within the specified time periods for each meal type. The start of each period was defined as the 25th percentile of the range of meal preparation start times in Leary, N Scott, *et al.* (2019) table 47. The end of each period was set as the 75th percentile of meal preparation start times plus the median cooking duration for that meal. The values used are shown in Table 19. The actual start times for a cooking appliance in any run of the model depend on the probability process that considers whether to start the appliance in each minute in turn. For some runs this will result in no use of the appliance for a meal: since there is only one eCook appliance considered in this case, this would result in no eCooking for that meal.

Table 19 Cooking periods, Tanzania

	Cases 1a and 1b	
	Start of period	**End of period**
Breakfast	06:14	08:54
Lunch	11:49	14:10
Dinner	17:21	20:14

4.2.2.3 Meals cooked with electricity

Given that the source of electricity is a mini-grid, this case looks at a transition to partial electric cooking, with households stacking an EPC with a traditional fuel. Based on review of the dishes typically cooked for each meal type (Leary et al, 2019d), meals are assumed to comprise the following appliances and cycles.

- Breakfast: no eCook; traditional fuels used
- Lunch: EPC, long use, cooking 50% of the meal, stacked with traditional fuel for the other 50%
- Dinner: EPC, long use, cooking 50% of the meal, stacked with traditional fuel for the other 50%

Even with just 50% of cooking transitioning to electricity (with just one appliance per kitchen), it was evident that the existing mini-grid capacity would be insufficient to support eCooking by all households. Preliminary network analysis suggested that around 10 households could safely transition, and that is the basis of the load modelling reported in the next section.

4.3 MECS household load modelling

The requirement for the mini-grid power system analysis is for a set of 88 households. As such the MECS demand model was run 22 times for each of the 4 household types (tier 1 and tier 2, each with and without daytime occupancy).

The model produces values for the electrical power for each of lighting, appliances and cooking, for each minute of the 24 hours, for each run of the model. A model run implements the various probability processes (affecting occupancy, lighting and appliance usage, cooking activity) and thus represents a unique instance of that household type. Ten households have transitioned to eCooking through provision of an EPC, with the typical usage as shown in section 4.2.2. Figure 24 shows the aggregate of 88 model runs, used to represent the aggregate load profile of the set of 88 households supplied by the mini-grid.

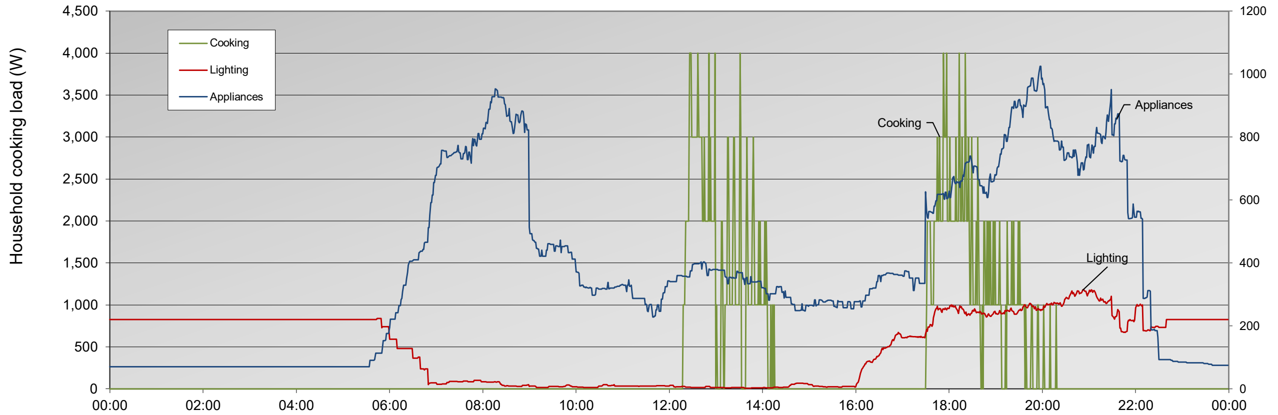


Figure 24 Aggregate load profile for 88 households, with and without eCook, Tanzania

The lighting load is almost zero during daylight hours. Overnight, the tier 2 households are assumed to have a security light in use. Lighting load peaks during the evening, as might be expected. The appliance loads are lowest at night, with only the baseload from the control units that connect each household to the mini-grid. Usage picks up around breakfast time and again in the evening, with lower use during the middle of the day, as 50% of the households are assumed to have no occupancy during the day and occupancy also reduces with some household members at work or school. The peak of the aggregate appliance load is just 1 kW for all 88 households, with peak of all non-cooking loads (appliances plus lighting) at around 1.2 kW. This equates to an average of 14 W per household at the peak of non-cooking electricity use. This may sound low, but the total non-cooking connected load for the tier 1 households is 27 W and for the tier 2 households is 84 W, and diversity in the timing of activities within and between households results in a much lower peak utilisation.

The cooking loads are concentrated into the two defined cooking periods. The peak is 4 kW, occurring both during lunch and dinner preparation periods; this equates to 400 W average per eCooking household at cooking peak. Given that most of the 10 eCooking households will for example be cooking dinner at some point during the 3 hour dinner period, an average of 400 W shows a considerable effect of diversity compared to the maximum peak of 10 kW that could be observed if all ten 1 kW EPCs were used simultaneously.

The overall ADMD from all uses of electricity is just below 5 kW, or 56 W per household.

Figure 25 shows the cumulative use of electricity over the day, for cooking and non-cooking (appliance + lighting) uses.

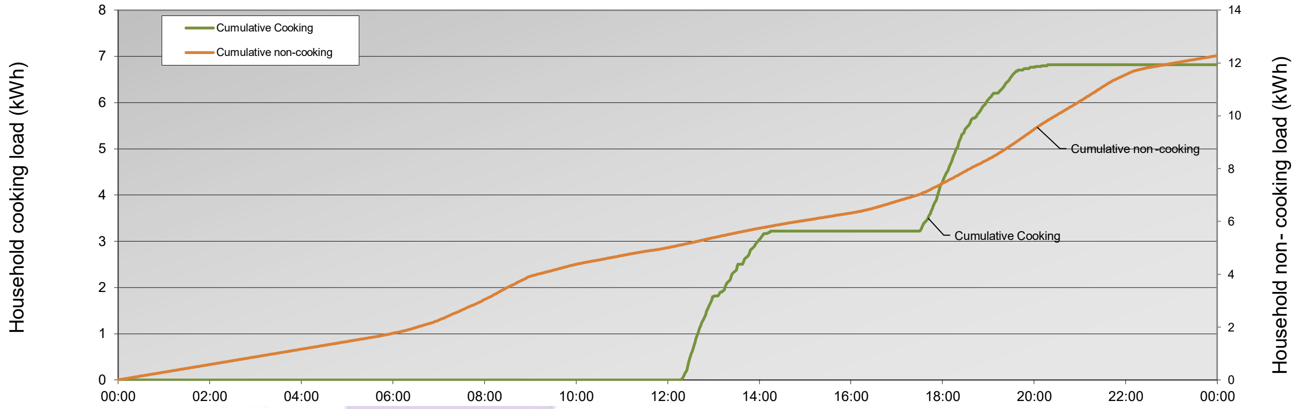


Figure 25 Cumulative load over the day for 88 households, Tanzania

Figure 10 summarises the shares of energy used for each purpose for the full set of 88 households over the day. For this mini-grid case, cooking electricity use is lower than in the Zambian grid-connected case, but the overall daily energy use for the 88 households is still quite balanced between cooking and non-cooking uses, since these are lower tier households and make less use of electricity for other services too. However this reflects the position that only 10 households are eCooking, and only then for 50% of their daily needs.

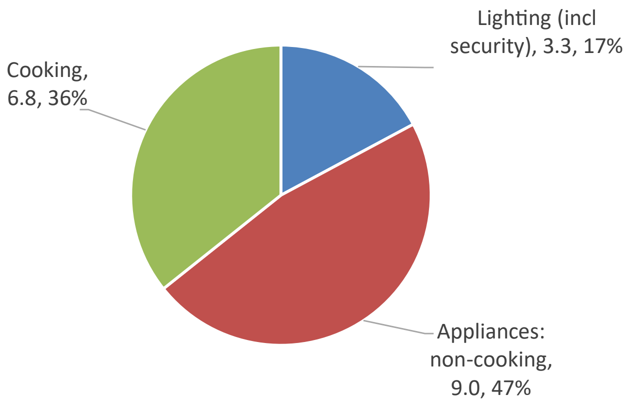


Figure 26 Shares of daily energy use for 88 households, Tanzania

Figure 27 shows the load profile for one example tier 1 household. The upper chart has a smaller scale to show the cooking loads and the lower chart is at larger scale so non-cooking loads can be seen. The EPC is used for both lunch and dinner. The 20 W fan is used twice. Lower power devices and lights are used intermittently.

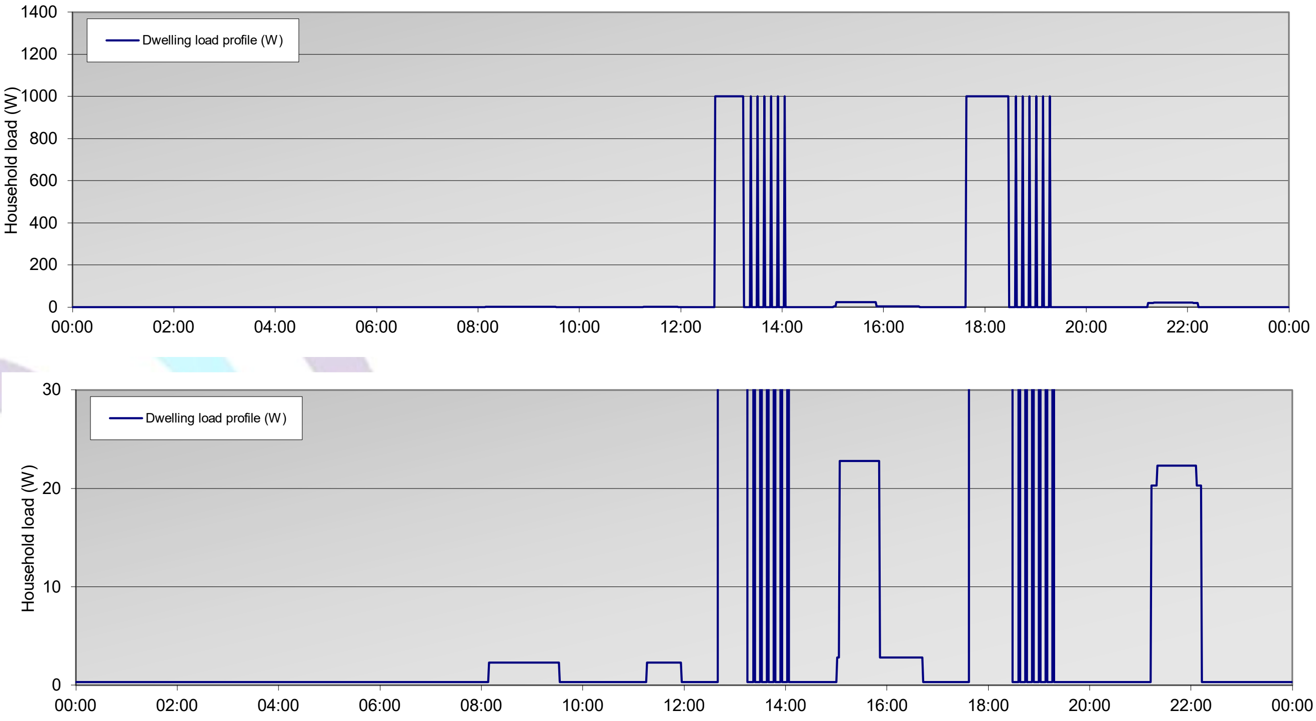


Figure 27 Load profile for one example household, Tanzania

Zooming into dinner time for this example household: as shown in Figure 28, the EPC starts at around 17.40 and is used at full power for around 45 minutes: this could include initial frying of ingredients and then the pre-heat stage (ie get up to temperature and pressure). The sharp spikes represent the EPC moving to its cycling after pre-heat: one minute on at 1 kW and then 7 mins off (following test lab evidence from CREST).

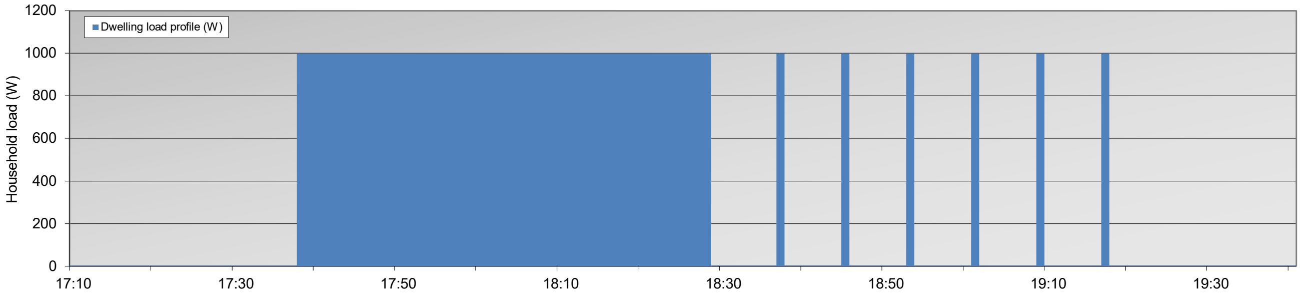


Figure 28 Dinner time for example household, Tanzania

4.4 eCook system design and costs

This case for mini-grid connected households in rural or peri-urban Tanzania equates to case study 4 in ESMAP (2020). The load modelling above and the power system analysis of section 4.5 consider just the 50% eCooking case, taken up by 10 households. However the eCook modelling here and the LCA in the next section consider both the case for a household taking up the 50% eCook scenario and also the costs and environmental impacts of a household moving to 100% eCooking. Cost and LCA results are provided for a 100% eCook case to illustrate the extreme scenario for a mini-grid context: considerable upgrades to the mini-grid would be required and these have not been modelled in the networks section.

Figure 29 reproduces the results charts from ESMAP (2020) and the results relevant for this case are shown circled in red: 50% AC eCooking, stacking with the relevant fuel (charcoal , LPG and firewood), compared with 100% use of charcoal, LPG or Firewood.

The assumed tariff for the mini-grid in this case study is $1.35/kWh, and hence with these assumptions eCooking is relatively expensive. The “clean fuel stack” of eCooking and LPG costs $12-21 per month, more expensive than the $6-12 required for charcoal alone but comparing favourably to $12-23 for LPG alone. However, mini-grid prices vary widely. ESMAP (2019) shows that in 2018 typical mini-grid tariffs internationally were $0.55–$0.83/kWh and they projected these falling to $0.25–$0.38/kWh by 2025. As ESMAP (2020) notes: “At these tariffs, it would be cost-effective for most peri-urban charcoal users to switch, as they would be paying $12 – $23/month. The cost of cooking solely with electricity would drop to $18 – $28/month, making it cost effective for consumers on mini grids in peri-urban areas with tariffs at the lower end of the range to switch to fully eCooking solutions”.

To move to the 100% eCooking scenario, included for the eCook modelling, although not a core part of the case for this study, the eCook system at the household end would just require purchase of a hotplate as well as an EPC. However to overcome the evident mini-grid capacity constraints (that led to even the 50% eCook case seeing transition of only 10 households) the 100% eCook scenario would require significant upgrade of the mini-grid. There are several options available including the installation of additional generation (likely solar PV in this case) and battery storage. These upgrades have not been fully costed, but the dashed red category in Figure 29 gives an indication of the upper-bound of the costs. This analysis, described in full in ESMAP (2020), considers adding the necessary battery storage at each house, as opposed to upgrading the mini-grid.

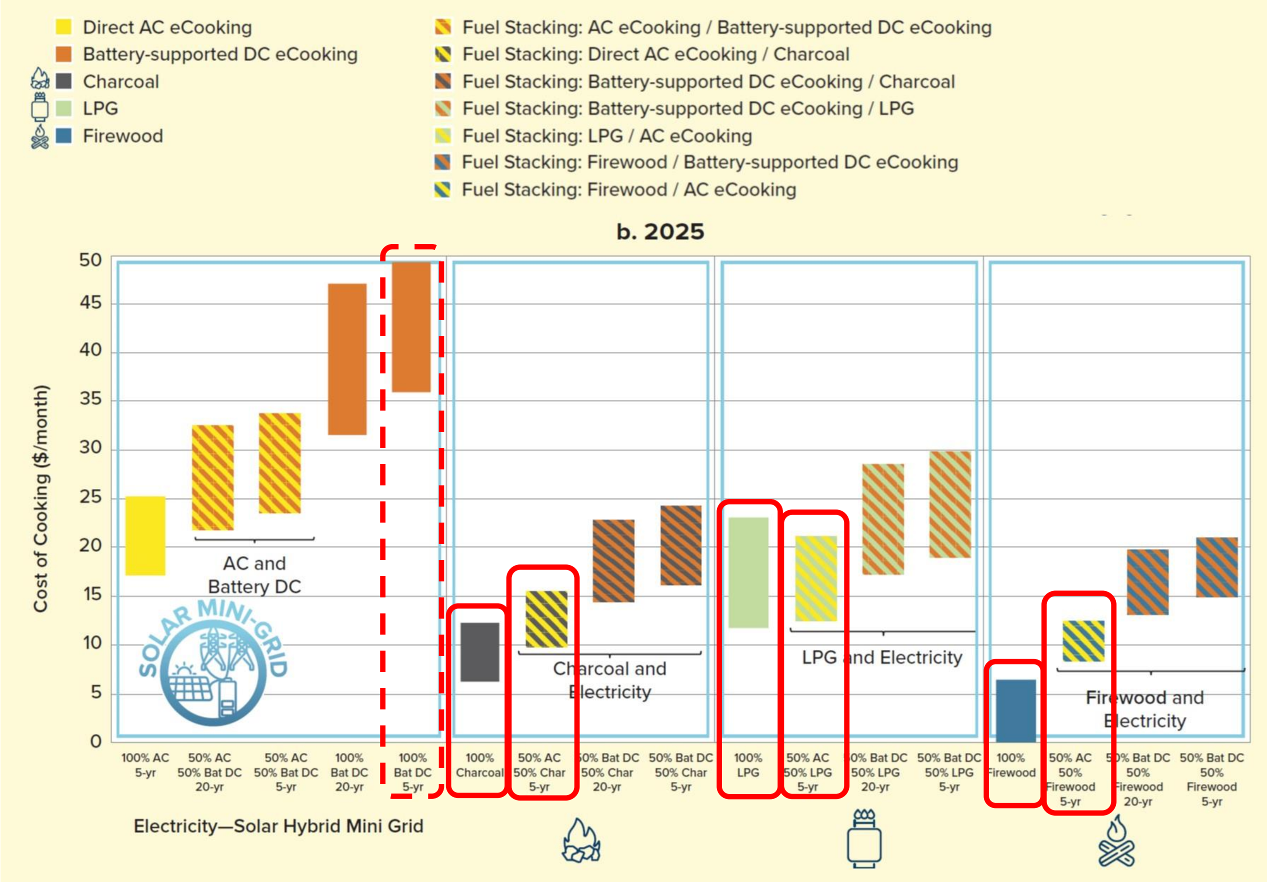


Figure 29 Tanzania case study results from ESMAP (2020)

4.5 Impact on existing electrical infrastructure

Out of several different solar mini-grid system providers in Tanzania (each introducing different system specifications), the model used to analyse the adoption of electric cooking devices was based on a specification provided by Powergen. As a company, they have already deployed EPC systems at the mini-grid level within several sites, specifically selected due to having adequate generating capacity headroom, and have proven that appropriate system operation can be maintained while providing electricity for the additional loading these cooking appliances bring. The layout of the mini-grid considered in this analysis is presented in Figure 30 (Williams *et al.*, 2017). It consists of 88 households supplied from a single generation and storage unit located in the central site on the system.

The mini-grid modelled was sized according to Powergen's specification. It is a three-phase AC system with an ABC cable of 50 mm^2 (this is the same specification as most LV distribution networks in sub-Saharan Africa, as explained in Section 2.4). The service lines are modelled as single-phase 16mm^2 ABC cables. The maximum power consumption allowed by a single household is 2 kW. The size of the inverter is matched according to the number of customers connected to the system. The standard module of 3 kW peak is typically installed for approximately 50 customers, which assumes demand diversity between households. Therefore, to simulate a mini-grid intended for 88 households, a 6 kW inverter was selected.

Figure 30 The Layout of the Powergen mini-grid

Off-grid mini-grid systems with a lower specification than that used by Powergen show limited capacity to support electric cooking demand. In this specification, this is due to the power inverter, PV arrays and battery banks being sized to serve only basic access to electricity - for lighting, phone charging, radios and TVs. Such appliances have substantially lower power and energy requirements than electric cooking devices.

To demonstrate feasibility for eCook adoption on mini-grid systems how the aggregate demand (after diversification) could potentially impact on the overall loading on the power inverter device needs to be analysed. The mini-grid is expected to experience power limitations while meeting new electric demand in this case. This is shown in Figure 31 where the relationship between number of households and the ADMD is provided.

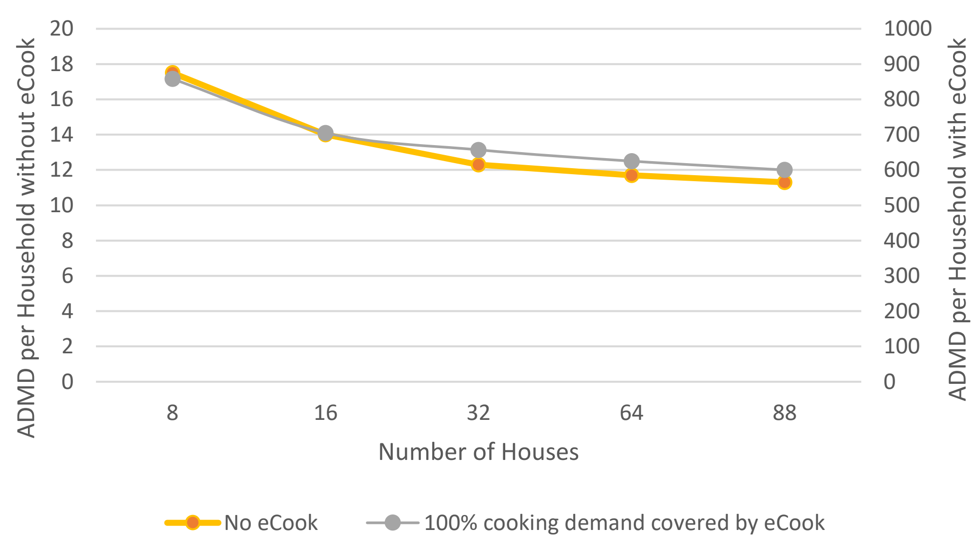


Figure 31 ADMD per Household before and after introduction of eCook for 100% of cooking load

The grey curve in Figure 31 shows that the cooking demand diversity for higher number of eCook users requires a lower inverter capacity per household compared with fewer eCook household, reducing from more than 800 W for a few customers to approximately 600 W if there are more than 64 customers.

Figure 31 also indicates that ADMD per household is around 12 W for 88 households without eCook. The aggregated ADMD for these 88 households without cooking devices is therefore approximately 1 kW. This confirms that for such a mini-grid supported by a 6 kW inverter, headroom to introduce clean electric cooking devices for 100% of cooking load exists for approximately 6 households.

Further analysis of demand profiles considering a single EPC unit installed at the household level covering approximately 50% of total cooking is summarized in Figure 32 illustrating relationship between ADMD per household and number of users with EPCs. The outcomes indicate that for the mini-grid system specified in the studies, up to 10 households could be equipped with EPCs without the need to upgrade the system.

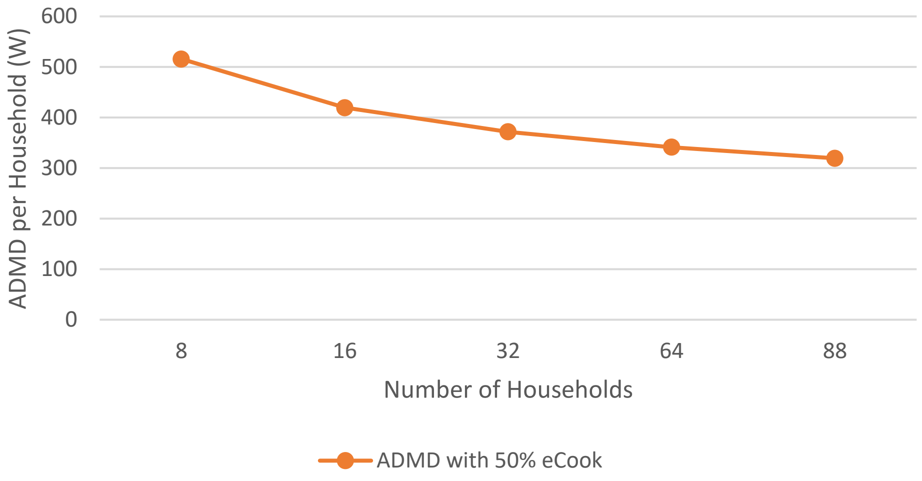


Figure 32 ADMD for Households covering 50% of cooking demand with EPCs

An example illustrating the daily demand profile within the mini-grid system presenting such a scenario is shown in Figure 33. The graph confirms that the introduction of eCook devices within the Powergen solar mini-grid could significantly increase the maximum demand required within the system.

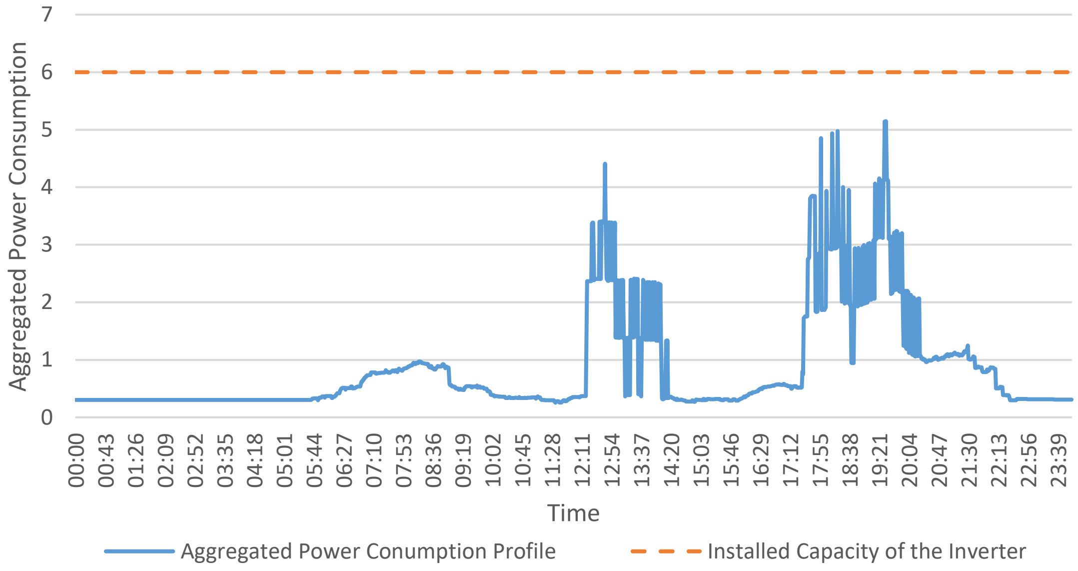


Figure 33 Mini-grid Demand after Introduction of eCook to 10 Households

Despite inverter limitations the results reveal that installed distribution networks can effectively support 100% of households with eCook devices without exceeding maximum network constraints. This is primarily due to the cables considered in the study being ‘overdesigned’. This is shown in terms of the voltage distribution across the mini-grid in Figure 34 with demand of 599 W at each household (average ADMD per household with 100% eCook penetration) which never exceeds maximum recommended 5% from the rated value. This high mini-grid distribution capacity potential implies that for constantly falling costs of PV systems, lithium-ion energy storage devices as well as power inverters, potential for introduction of eCook on off-grid solar mini-grids is expected to increase in the coming years.

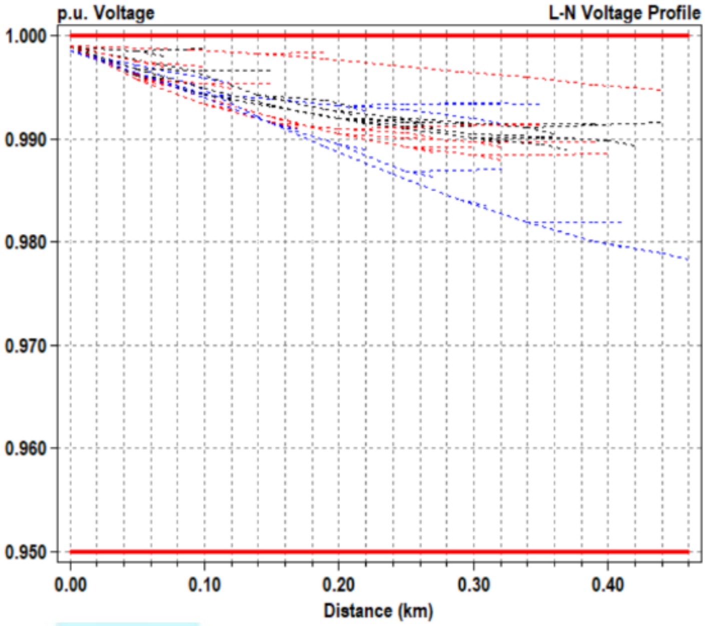


Figure 34 Voltage Profiles under ADMD of 599W

4.6 Environmental impact

Figure 35 shows the system diagram for case study 2, a Mini-grid system in Tanzania, and Table 20 shows the options evaluated. As for case 1, the fuel use values are scaled up from the original data in Table 6 – which are normalised for a 4.2 person household - to reflect the modelling results for the household sizes in this case.

Table 20 Options evaluated for Scenario 2, Tanzania

Scenario	Devices	Quantity per household per day		
100% Charcoal	Ceramic Jiko	1.88 kg charcoal		
100% LPG	2 Ring LPG burner	0.35 kg LPG		
100% Wood	TSFP	3.72 kg wood		
50% Mini-grid, 50% Charcoal	Ceramic Jiko sEPC (electric pressure cooker)	PV array, 905 m2 Inverter, 47.2 kW	LFP Battery, 138 kWh 0.93 kg charcoal	Efficiency of PV panels assumed to 16%.
50% Mini-grid, 50% LPG	2 Ring LPG burner sEPC	PV array, 905 m2 Inverter, 47.2 kW	LFP Battery, 138 kWh 0.175 kg LPG	Efficiency of PV panels assumed to 16%
50% Mini-grid, 50% Wood	TSFP sEPC	PV array, 905 m2 Inverter, 47.2 kW	LFP Battery, 138 kWh 1.86 kg wood	Efficiency of PV panels assumed to 16%
100% Mini-grid	sEPC Hotplate	PV array, 1705 m2 Inverter, 98.2 kW	LFP Battery, 249 kWh	Efficiency of PV panels assumed to 16%
100% Mini-grid with Diesel generator	SEPC Hotplate	PV array, 944 m2 Inverter, 54.6 kW 88 kW diesel generator operating for 0.01272 hours per day on average	LFP Battery, 165.6 kWh	Efficiency of PV panels assumed to 16%

A mini-grid provides power for a range of functions, lighting, other electrical appliances such as fridges and TV's, charging capability and potentially for cooking. Mini-grids in developing countries are typically built to provide relatively low power uses, and are not designed with cooking in mind. This environmental assessment evaluates the environmental impact of a case study mini-grid from two perspectives; for cooking only, and for the combined services the mini-grid provides. For each case, the proportion of the mini-grid capacity that is used to provide the function under investigation is assigned to the system, e.g. for cooking only, only the proportion of the mini-grid that is needed for cooking is assigned to the cooking system. These two perspectives can provide an understanding of the best uses for mini-grid electricity, and the importance of correct sizing.

Figure 36 shows the contribution of the components of a mini-grid to the midpoint impact categories. The PV panels dominate all the categories, except for human carcinogenic toxicity. Here, the group 'Energy, Mgrid' dominates. This group contains the rest of the components that are needed to physically deliver the mini-grid system, such as cables, poles, fixings, PVC components etc. The cause of the spike within human carcinogenic toxicity is the chromium-based preservative used on the wooden poles and stay-blocks, and a switch to concrete for these items significantly reduces this impact.

It should also be noted that the impacts associated with the inclusion of a diesel generator are so small as to not show up on the graph. However, the inclusion of the diesel generator is important, as it allows for a significant reduction in the number of PV panels required to meet loads, and reduced LFP battery sizes.

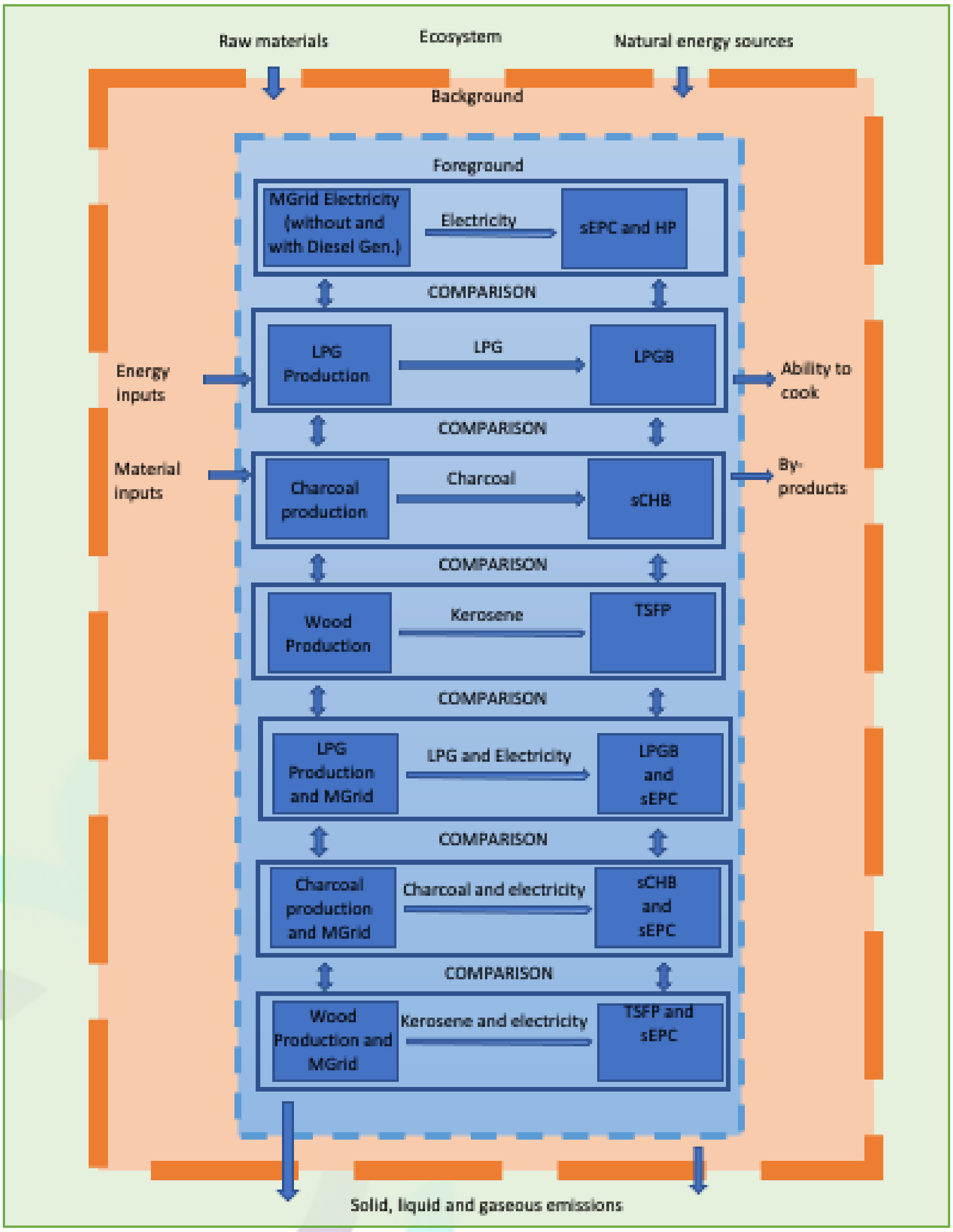
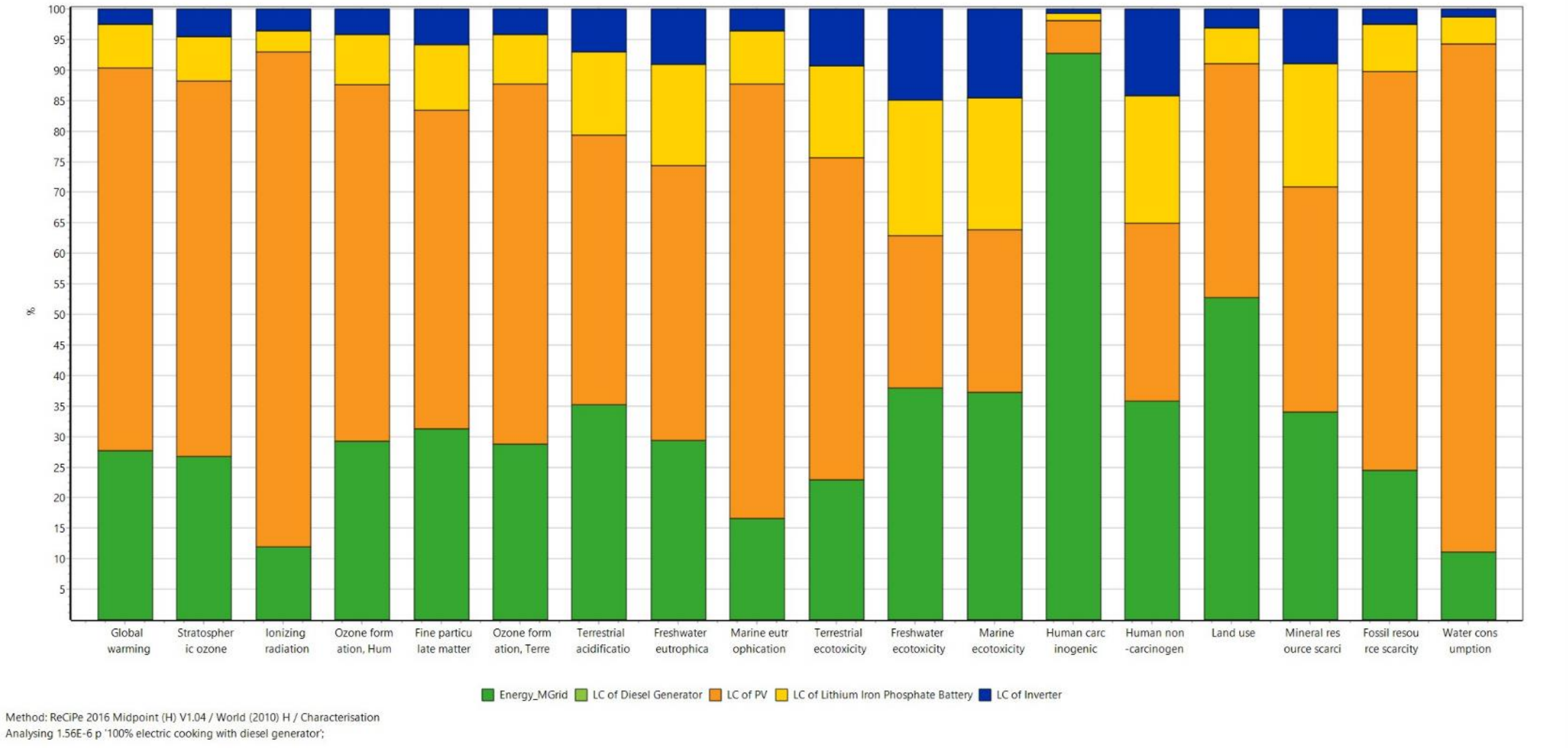


Figure 35 System diagram for mini-grid cooking in Tanzania



Method: ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H / Characterisation
Analysing 1.56E-6 p '100% electric cooking with diesel generator';

Figure 36 Contribution analysis of the components of a Mini-grid

4.6.1 Mini-grid for cooking only

Given that cooking will represent the majority of the power supplied by the mini-grid, this first of two assessment options allocates all of the environmental impacts associated with the construction and operation of the mini-grid to the electric cooking it delivers. Figure 37 shows the environmental midpoint categories for different methods of providing cooking in Tanzania, for the following scenarios:

- Traditional fuels (charcoal, wood and LPG),
- A 50:50 split of traditional fuel with electrical cooking powered by a mini-grid,
- 100% electrical cooking from the mini-grid powered by PV only, and
- 100% electrical cooking powered by the mini-grid supported by a diesel generator.

The two final scenarios for 100% electric cooking are for illustration only but they represent scenarios that will need to be realised at some point if Tanzania is to meet zero carbon commitments in the future. This highlights the opportunities and impacts that would need to be considered should this scenario become a preferred option.

Figure 37 shows that wood and charcoal tend to dominate the climate change, stratospheric ozone, ozone formation, particulates and acidification, whereas the mini-grid dominates the toxicity impact categories. For charcoal and LPG, the reasons are as for case study 1, Zambia. For wood and the mini-grid, the impact on the main midpoint categories of interest to MECS are given below.

For climate change:

- For 100% wood cooking and for 50% wood with 50% mini-grid cooking, climate change is driven by the combustion of the wood in the home.
- For the 100% PV mini-grid and 100% Mini-grid backed up with a diesel generator, climate change is driven by hard coal mining in China, and heat production form industrial coal furnaces, again in China. This can be linked to electricity production used to manufacture PV arrays and batteries.

For particulate formation:

- For 100% wood cooking, again the cause of particulate emissions can be traced to combustion of wood in the home. This is of particular concern for associated health impacts of particulate inhalation.
- For 50% wood with 50% mini-grid cooking, particulate emission is caused not only from the combustion of wood in the home, but also from production of primary copper (needed for mini-grid manufacture).
- For the 100% PV mini-grid and 100% Mini-grid backed up by a diesel generator, the causes of particulate emissions are production of primary copper and the generation of high voltage electricity from lignite.

For human carcinogenic toxicity:

- For 100% wood cooking, the main driver of human carcinogenic toxicity is landfill of slag from steel furnaces. This comes from forest management activities, which use using large machinery.
- For 50% wood with 50% mini-grid cooking, the 100% PV mini-grid and the 100% Mini-grid backed up by a diesel generator; the primary driver is the treatment by landfill of slag from steel furnaces, and the treatment of red mud from bauxite digestion. The use of steel in supporting systems for PV pane production and aluminium in the frames for PV panels are the likely causes for these impacts.

For human non-carcinogenic toxicity:

- For 100% wood cooking, the main driver of human non-carcinogenic toxicity is zinc, found in residue from car shredding. This is most likely linked to background systems supporting production of wood.
- For 50% wood with 50% mini-grid cooking, the 100% PV mini-grid and the 100% Mini-grid backed up with a diesel generator, treatment of sulphidic tailings and the production of primary copper are the main drivers on human non-carcinogenic toxicity. Again, this results from the production of copper, found in the supporting equipment for a mini-grid, in wires, cables and circuit boards.

Once again, normalised impact categories show the toxicity categories of greatest impact (Figure 38).

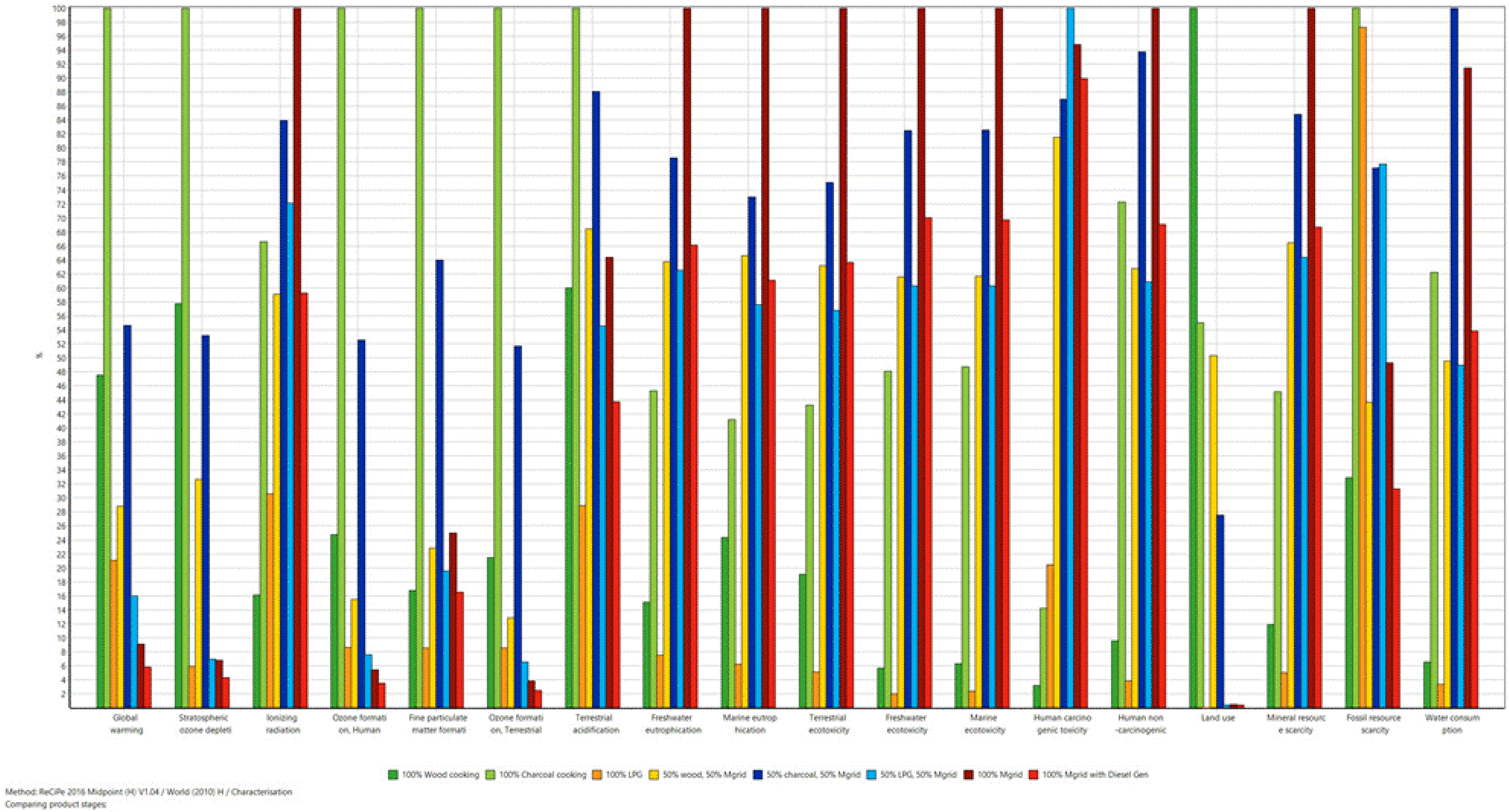
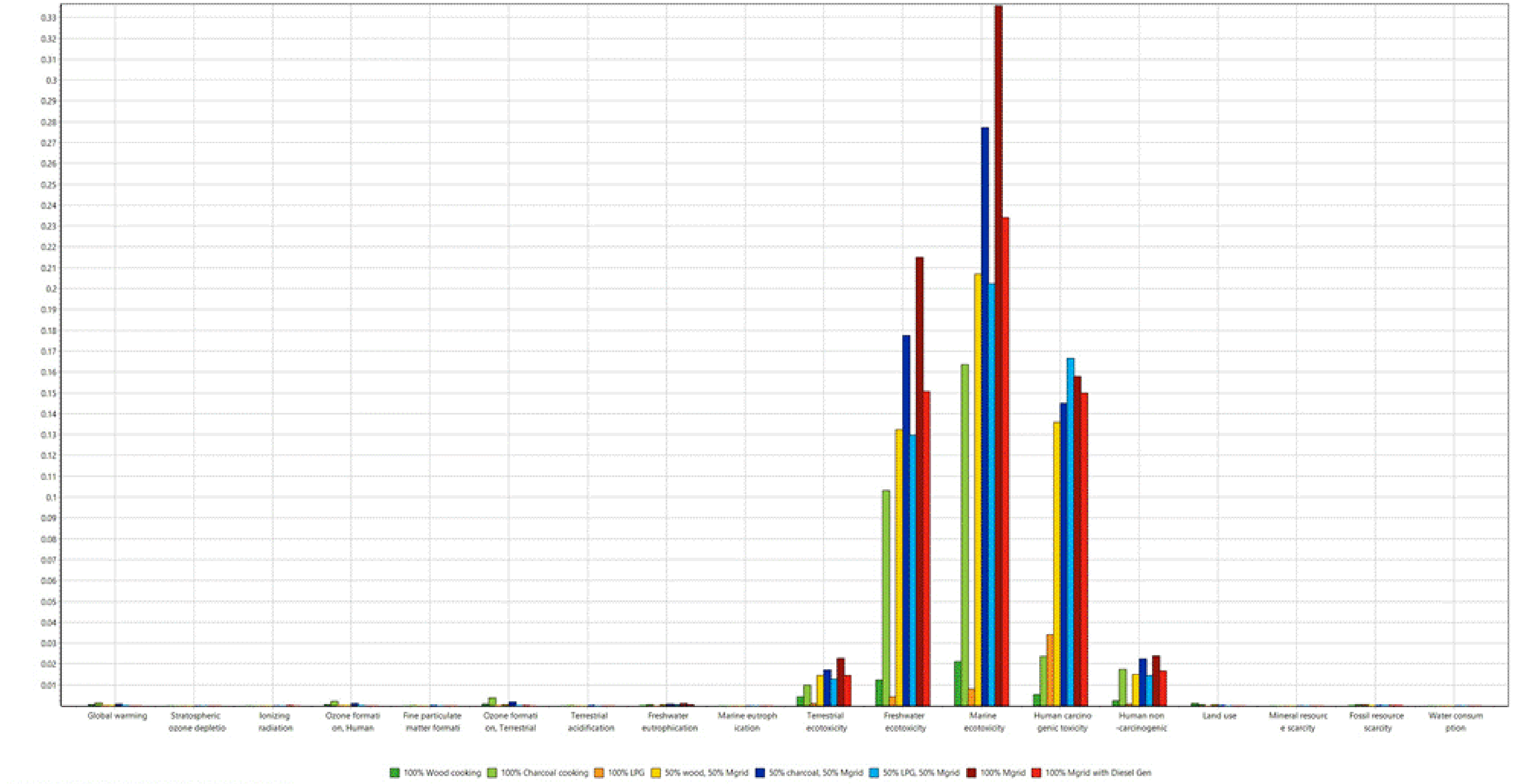


Figure 37 Midpoint impact category results for different cooking options in Tanzania



Method: ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H / Normalisation
Comparing product stages

Figure 38 Normalised midpoint impact categories for different cooking options

Considering the end point impact categories, of human heath, ecosystems and resource use, Figure 39 shows the damage for each cooking option. Once again, charcoal cooking is seen to come out worst with high scores for each of the categories. LPG shows the worst score for resources. The damage from the mini-grid both with and without the diesel generator is generally lower than that for traditional fuels.

Figure 40 shows the aggregated impacts for each cooking option, combined into a single score. This shows that for those cooking with charcoal, a switch to a mixed electrical and traditional based fuel cooking system is appropriate, and further improvements can be made by switching to 100% electrical cooking, either purely with PV generated power, or by a PV and diesel generator hybrid mini-grid.

For wood, there is only a marginal improvement to be realised by switching to a mixed wood and electrical system. However, significant benefits can be seen if moved to a fully electrical cooking system, again either as 100%PV powered or a mixed diesel generator, PV hybrid system.

For LPG, the results do not follow the same pattern. In all cases where a mini-grid is used to provide some electrical power for cooking, the overall benefits are seen to be worse than 100% LPG. This is due to the fact that the 'impact per unit cooking' for the mini-grid systems are worse than the 'impact per unit cooking' for the LPG system.

An additional scenario investigated for the mini-grid was to exchange the wooden poles and stay block (preserved using a chromium-based solution with high human carcinogenic toxicity) for concrete poles and stay blocks, to see if this would improve the 'impact per unit cooking' for the mini-grid systems. The results are presented in Table 21, where it can be seen that the change to concrete poles delivers a significant benefit, but not enough to reduce the impact of a PV only mini-grid system to below that of the LPG cooking system. The only case where the mini-grid outperforms LPG is when it is combined with a diesel generator.

Table 21 Comparing endpoint impacts: chromium based preserved wood poles vs concrete poles

		Unit	100% LPG	50% LPG and 50% electric cooking	100% electric cooking	100% electric cooking with diesel generator
Wooden poles and stay blocks	Human Health	mPt	48.7	79.8	78.1	58.8
	Ecosystems	mPt	4.2	3.9	3.0	2.0
	Resources	mPt	1.5	1.0	0.4	0.3
	Total	**mPt**	**54.4**	**84.7**	**81.5**	**61.1**
Concrete poles and stay blocks	Human Health	mPt	48.7	59.6	55.2	35.9
	Ecosystems	mPt	4.2	3.7	2.8	1.8
	Resources	mPt	1.5	1.0	0.4	0.3
	Total	**mPt**	**54.4**	**64.3**	**58.5**	**38.0**

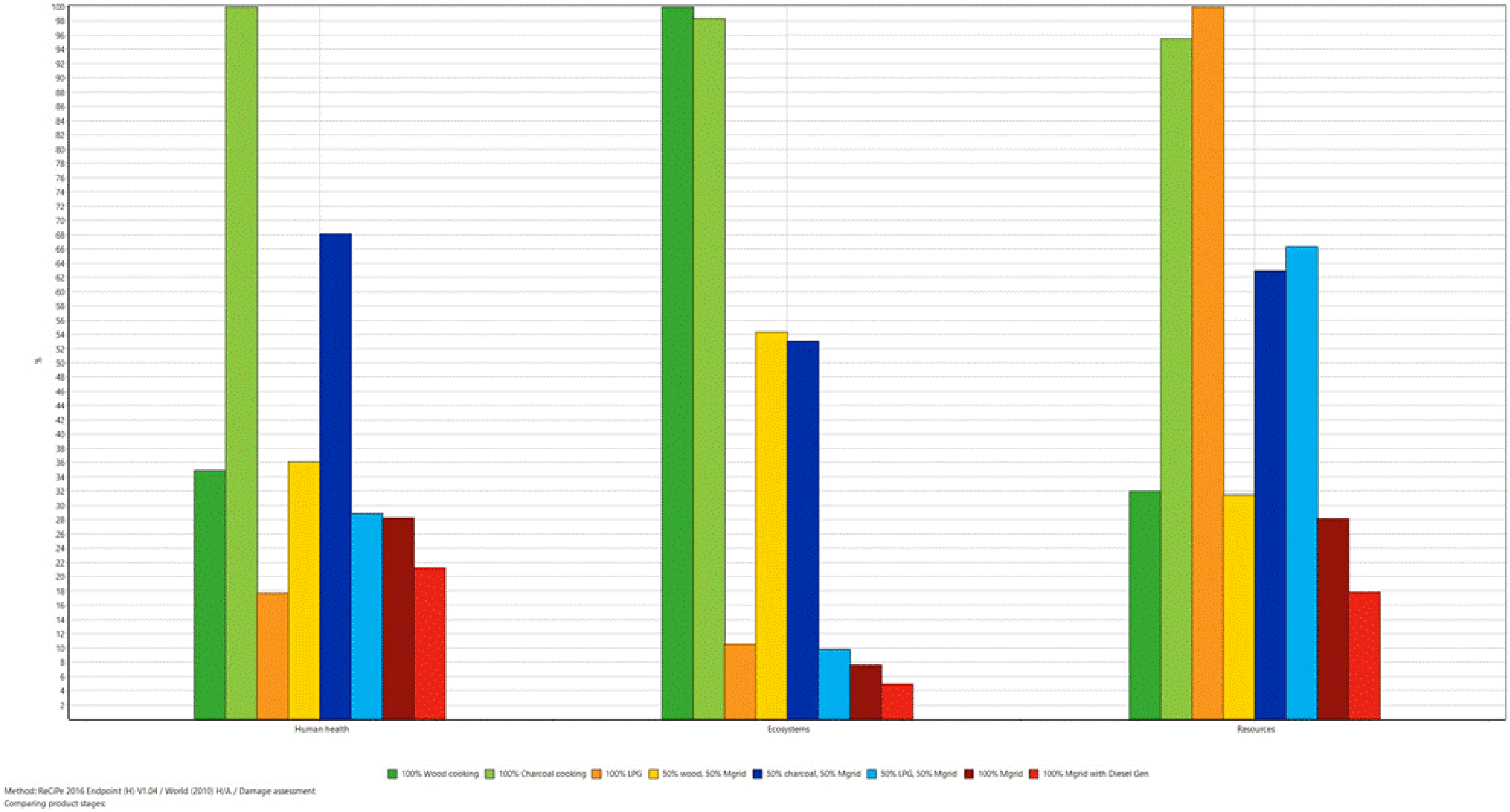
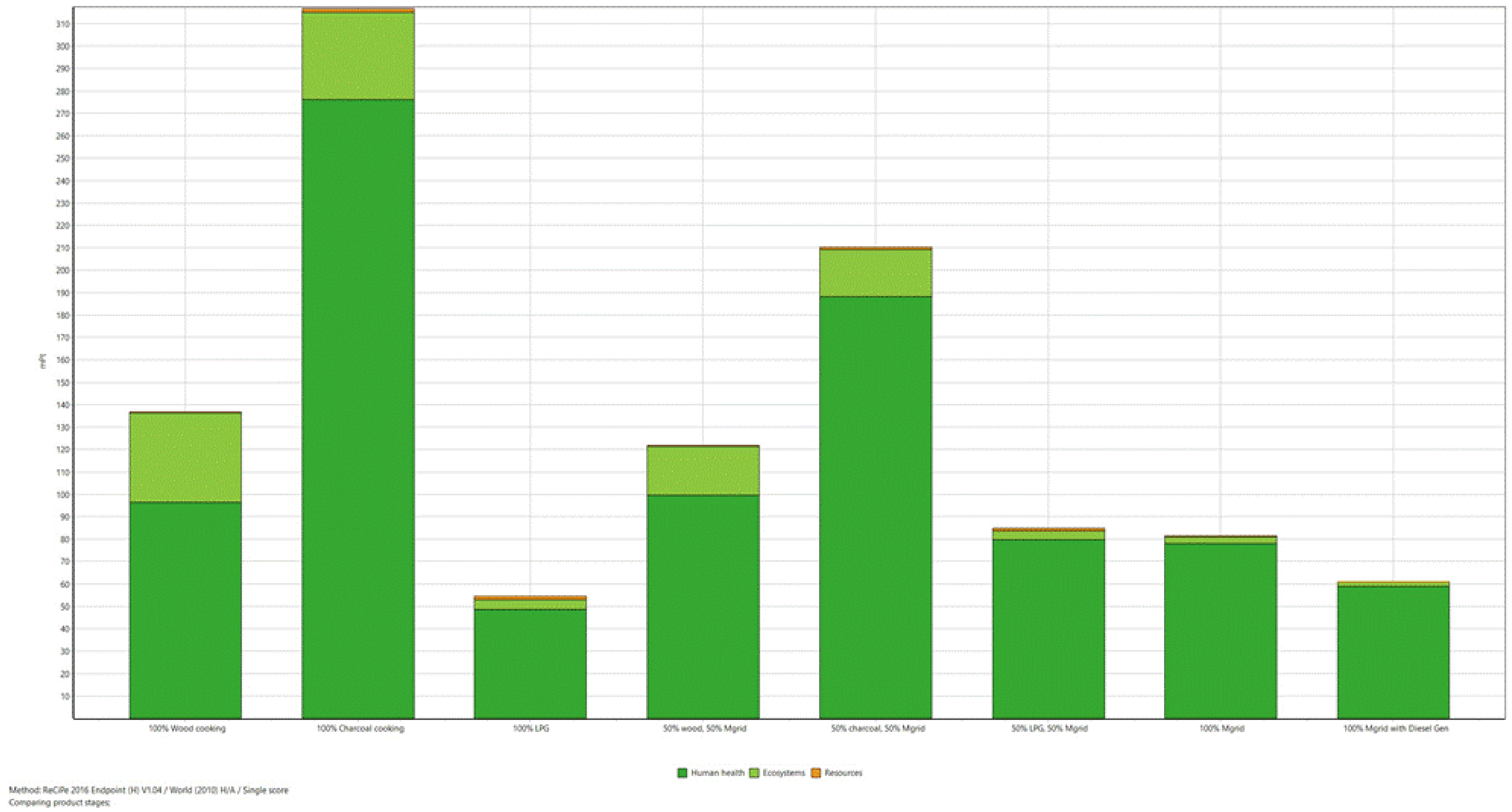


Figure 39 Endpoint damage assessment for cooking options



Method: ReCiPe 2016 Endpoint (H) V1.04 / World (2010) H/A / Single score
Comparing product stages;

Figure 40 Aggregated endpoint impacts for cooking options in Tanzania case

4.6.2 Mini-grid for cooking and other electrical activities

At its lowest level a mini-grid in a developing country would typically be built to provide lighting and other non-cooking energy services. As such the initial analysis in section 4.6.1, allocating the mini-grid impacts to eCooking alone, is an extreme case. Using the load results of section 4.3, the impacts can instead be allocated between cooking and non-cooking electricity services. Impact allocation in LCA is however not a simple or uncontentious process. Some alternative formulations are proposed below, seeking to produce broadly comparable scenarios, with and without eCooking, whose impacts can be compared.

The intention is to create scenarios that compare the impacts associated with energy-using activities for the group of households, firstly without eCooking, and then after eCooking has been introduced. The existing mini-grid is initially providing only non-cooking energy services (lighting, phone charging, entertainment). The load analysis shows that once eCooking is added, up to the power capacity limits of the mini-grid, approximately 36% of the energy supply from the mini-grid is used for cooking, and 64% for non-cooking services. This share of electricity supply is used to allocate the impacts of the mini-grid between the different services it can provide. The scenarios assessed are:

- Before eCooking: 100% of cooking using one of the traditional fuels (wood, charcoal or LPG); plus the mini-grid used for non-cooking energy services (allocating 64% of the total mini-grid impacts)
- eCooking by 10 households is provided using the ‘spare’ capacity on the mini-grid, e.g. eCooking by 10 households for 50% of their cooking, plus traditional fuels used for the remainder of their cooking needs. The remaining 78 households use traditional fuels for 100% of their cooking needs. All households use power provided by the mini-grid to meet their lighting and other appliance requirements.
- The mini-grid is resized to provide sufficient power for all 88 houses to meet 50% of their cooking needs, plus electricity t power lights and other appliances. The residual cooking needs are met using traditional fuels
- The mini-grid is re-sized to support 100% electric cooking, using PV and batteries alone, plus lighting and other appliances
- The mini-grid is re-sized to support 100% electric cooking, plus lighting and other appliances), but with a mixture of PV/batteries and a diesel generator (and hence a smaller increase in PV and battery capacity than for the previous scenario)

Similar to the results for the midpoint indicator category (Figure 41) for the cooking system alone, charcoal and wood dominate for climate change, acidification etc, and the mini-grid tends to dominate in the toxicity impact categories. Figure 42 shows the damage on human health, ecosystems and resource consumption for each option.

This shows LPG options as causing high resource use impacts, and 100% electrical options amongst the lowest impacts for the three endpoints. Again, like the cooking only scenario, it is the human health impacts that are seen to be the greatest when the endpoint impact categories are normalised. The aggregated single score results are shown in Figure 43.

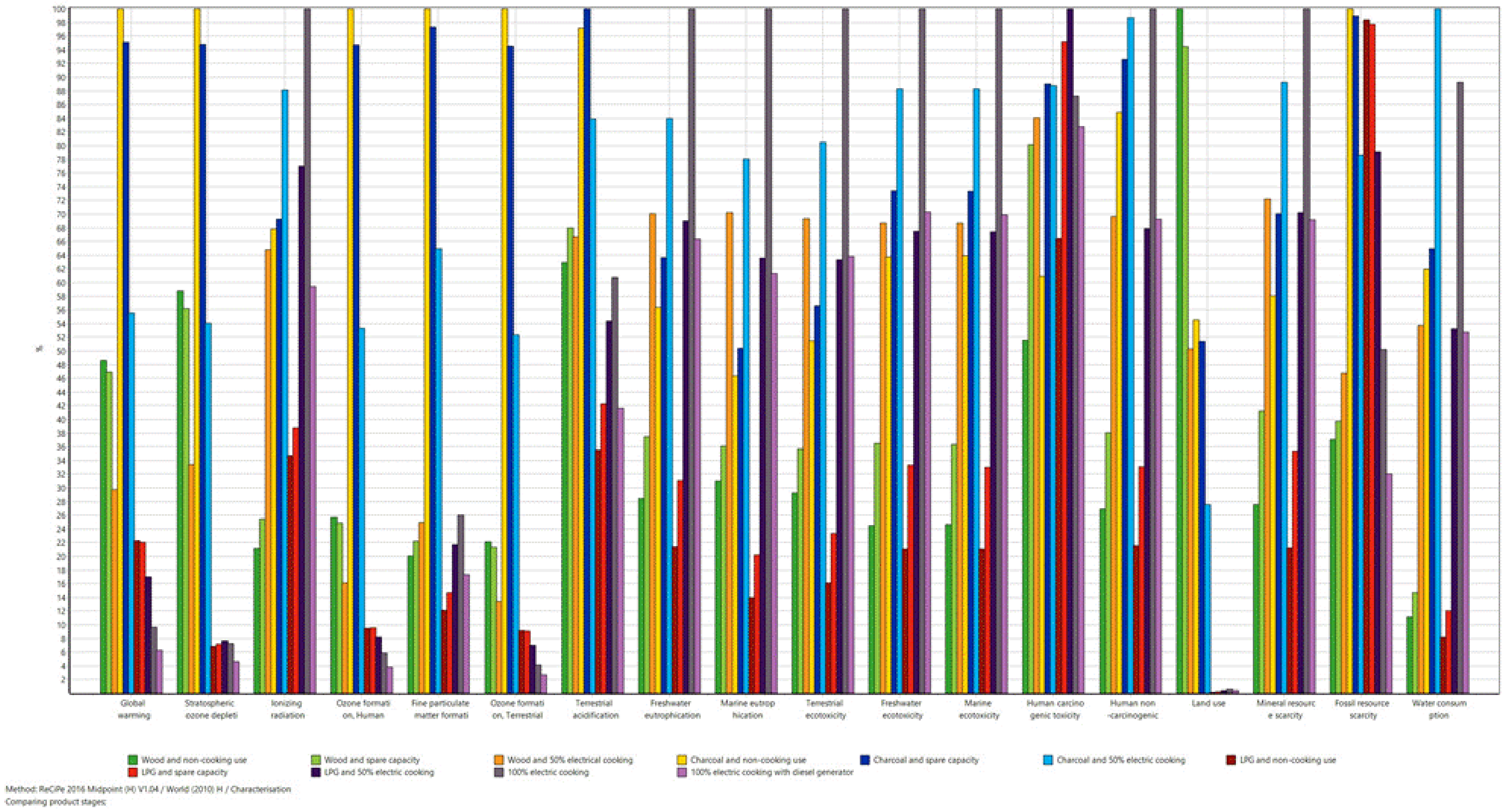


Figure 41 Midpoint indicator category results for mini-grid for cooking and other activities

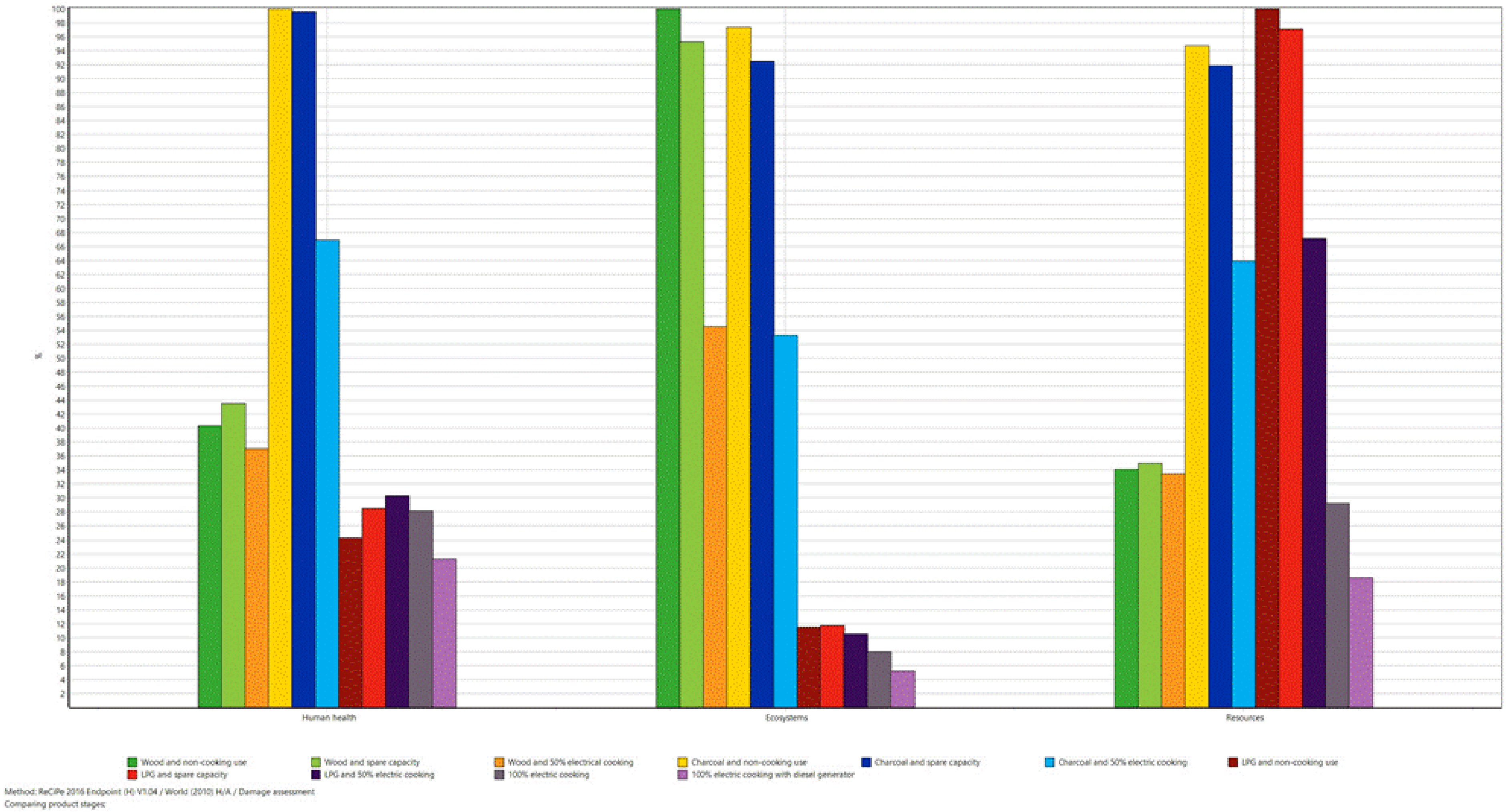


Figure 42 Damage to endpoint categories for mini-grid for cooking and other activities, Tanzania

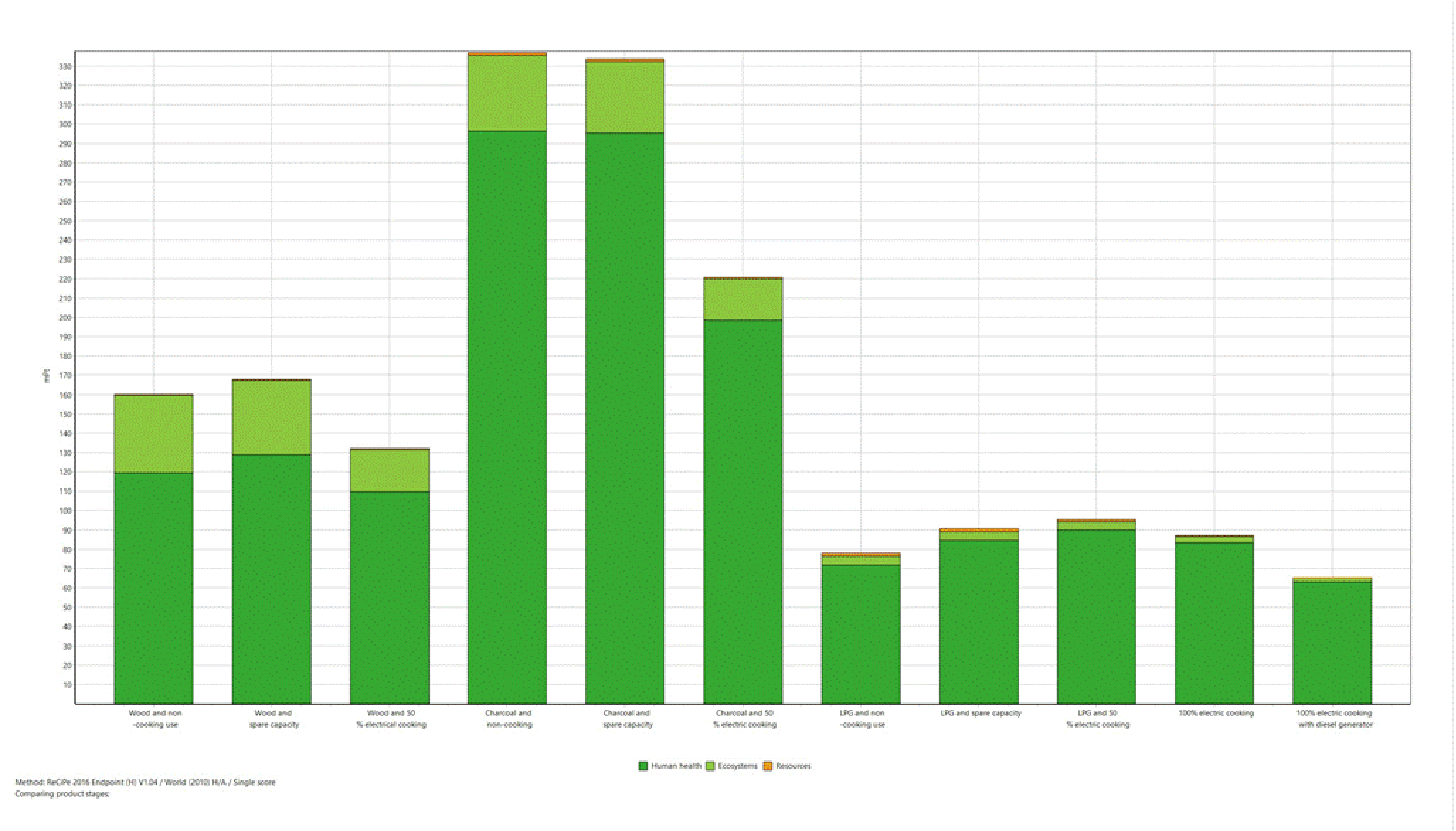


Figure 43 Aggregated single score endpoint categories for cooking and other activity options

For charcoal, it can again be seen that combining the mini-grid in any combination with charcoal cooking will deliver an improved environmental performance, although the biggest improvements can be seen when the mini-grid is sized to provide either 50% or 100% of the cooking and other activities. Looking at the options containing wood, using wood for all cooking and allocating only that part of the mini grid that is used for providing lighting and other activities (64% of the mini-grid impacts) appears to have a lower impact than reducing wood use by utilising the spare capacity of the grid for cooking. This is because again, the 'impact per unit cooking and other activities' from the grid, is greater than the 'impact per unit cooking' for wood. For LPG, in a similar manner to the cooking only results, it appears that combining LPG with a mini-grid delivers a reduction in environmental performance for all options, except when using a mini-grid in combination with a diesel generator.

It could be argued that 100% of the mini-grid impact should be allocated to lighting and other activities (rather than 64%), as the infrastructure is already in place. The red ovals in Figure 44 highlight the benefit to be gained in utilising the existing spare capacity of the mini-grid for cooking, assuming that all the environmental impact from the grid is assigned to the non-cooking activities. The red ovals show the benefits for each fuel option, wood, charcoal and LPG. For wood, the benefit is positive, but marginal. For charcoal, the benefit is significant, and for LPG the benefit is extremely small.

The different ways of allocating the impacts from the mini-grid (proportionally between the cooking and non - cooking load, or all allocated to the non-cooking load) do not change the physical environmental impact of the system, merely the values according to an arbitrary functional unit.

4.6.3 Summary of environmental impacts

The majority of the drivers or causes for the impacts associated with the different cooking systems are outside the direct control of the users of mini-grids, or even the intermediaries who supply components. The production of batteries, PV arrays, cabling or LPG are generally through global supply chains, and cannot be easily influenced (or, in some cases even accurately identified). In order to reduce the impact from the different cooking options, the contribution of components to overall impact is important. This can identify those items that are the cause of most concern, and direct modifications for improvement. In the case of mini-grids, the following issues should be considered as possible ways to reduce their impact, and support the move towards clean cooking:

- Swap wooden poles for locally made concrete poles and stay blocks. If this is not possible, then a non-chromium based preserving solution should be used.
- Combine a diesel generator with PV cells to reduce quantity of cells and associated equipment.
- To eliminate the combustion of fossil fuels in the diesel generator, consider using biofuel to power the generator. It is used relatively lightly, and local organic waste streams/agricultural waste could be considered as local feedstock.
- Employ the most efficient PV panel systems available to reduce quantity needed, and ensure these are always working at optimum efficiency (e.g. clean and dust free).

The current model results of the environmental assessment show that for charcoal users, a switch to electric cooking from a mini-grid will provide environmental improvement. For wood users, the benefits are marginal if utilising spare capacity, but substantial if a mini-grid is sized appropriately to provide for both cooking and lighting and other accessories. For LPG users, the benefits only become apparent when a PV mini-grid is supported by a diesel generator, given current levels of PV technology.

Method: ReCiPe 2016 Endpoint (H) V1.04 / World (2010) H/A / Single score
Comparing product stages;

Figure 44 Aggregated endpoint impacts: environmental impacts assigned to non-cooking activities

4.7 Case 2: summary findings

This second case study explores the potential for households connected to a solar-diesel hybrid mini-grid in rural or peri-urban Tanzania that provides them with lighting, phone charging and entertainment services; but they are initially cooking with biomass or LPG. The mini-grid supplying 88 households is found to have the capacity to support around 10 households using an EPC and the case study explores the contributions and impacts of this partial transition to eCooking.

The findings from application of the demand, eCook, LCA and network models show that:

- Households are at tiers 1 to 2, and hence have only a few appliances: lights, phone chargers, small sized radios and TVs, and some have a fan and security lights. These appliances total to between 30 and 90 W per household. After diversity effects in the timing of appliance use and household occupancy, the expected peak in daily load from the group is just 1.2 kW, or 14 W per household. Non-cooking electricity use averages to between 60 and 240 Wh/household per day
- If 10 households transition to eCooking with a 1 kW EPC, after diversity effects in the choices of meals and occupancy, the total electricity use per day for the group of 88 households will increase by more than 50%. Diversity also affects the timing of cooking (for example across the 3 hour window observed for dinner preparation), and the peak of the aggregate cooking load is equivalent to only 400 W per eCooking household. Overall the peak aggregate load drawn from the grid will increase to 5 kW, a factor of four increase.
- Since it was evident that the mini-grid would not be able to support eCooking by every household, some initial analysis was done to define the scenario of 10 eCooking households. Hence it is not surprising that the full power system analysis shows that the mini-grid with its 6 kW inverter can support this level of eCooking. The analysis of voltage distribution also shows however that the installed distribution network is capable of supporting eCooking for all households, although it would then require upgrade of the PV and battery capacities.
- The mini-grid modelled for Tanzania has quite high tariffs, and hence cooking is relatively expensive. The eCook modelling however showed it could compete with LPG, and could be equivalent cost to charcoal in some circumstances. A ‘clean fuel stack’ of EPC plus LPG could offer an attractive package and a route into eCooking. However mini-grid tariffs are expected to fall, and based on the World Bank’s projections it could become cost effective to transition to 100% eCooking.
- The environmental assessment shows that for charcoal users, any switch to electric cooking using a mini-grid will provide environmental improvement. For LPG users, the benefits only become apparent when a PV mini-grid is supported by a diesel generator, given current levels of PV technology. However the allocation of impacts between cooking and non-cooking services provided by a mini-grid is complex, and analysis of further alternative scenarios would be useful. The LCA also highlights the potential for high levels of human or environmental impacts from particular processes along the supply chain for infrastructure such as a mini-grid: in this case the preservative assumed to be used for distribution network poles has significant human toxicity. This ‘hotspot’ analysis helps improve design.
- The current reality is that mini-grids are designed without cooking in mind, and if some eCooking can be achieved using ‘spare’ capacity of the existing infrastructure, that will come with very low additional impacts. This study has not looked closely at the design of mini-grids with eCooking as a key objective. However the load analysis results suggest that the diversity in timing of appliance use will lead to

aggregate peak loads well below the rated capacity of connected loads, and thus the additional mini-grid capacity and associated costs and impacts will be moderated.

In conclusion, the sort of mini-grid supplying tier 1 and 2 energy access in Tanzania might well have capacity to support some limited eCooking, with low environmental impacts, and with manageable, and falling, costs. As PV and battery prices continue to reduce, the opportunities to design mini-grids for more widespread use of eCooking look positive.

5. Case 3: off-grid cooking in Kenya

5.1 Outline of the case

This third and final case explores the provision of eCooking for off-grid households in rural Kenya, through standalone solar PV plus battery power systems for each individual household. The analysis and modelling for this case differs from the previous ones: with no pre-existing use of electricity for non-cooking services, there is no need to analyse this baseline load; and there is no grid connection and hence no need for network modelling. Instead the focus is on the application of the eCook model to size the PV and batteries required, and then the LCA for environmental impacts of that system, compared to cooking with traditional fuels.

5.2 eCook system design and costs

This case for off grid eCooking in rural Kenya equates to case study 5 in ESMAP (2020a), focused on a scenario of either 50% or 100% replacement of traditional fuels with eCooking. The 'eCook system' in this case is more extensive than for the earlier cases, starting with solar PV, feeding into a Lithium Iron Phosphate Battery (LFP) and then to a range of DC electric cooking appliances, with power flows managed by a set of controllers. Figure 5 provides a schematic of how this is modelled.

Figure 45 reproduces one of the results charts from ESMAP (2020). The results for this case are circled in red: 100% DC cooking using a mixture of EPCs and hotplates or 50% DC cooking using just an EPC and stacking, compared with use of charcoal, LPG or firewood.

Figure 45 Kenya case study results from ESMAP (2020)

Biomass prices in the region are already high (assumed to be $0.31/kg, as discussed in ESMAP (2020)), and with assumed price increases of 5% per year by 2025 50% eCooking with fuel stacking with charcoal or firewood is cost effective. The 100% eCooking scenario can compete if charcoal prices are in the upper half of the modelled range, even for the business model using a 5 year financing horizon. The least expensive option is LPG. However, stacking with partial eCook would not increase costs to the user very significantly, and would bring valuable co-benefits: the PV-battery system would easily provide non-cooking energy services such as some lighting, phone charging and entertainment, for households assumed to be otherwise without access to modern energy.

Unlike the other cases in this study, cooking with electricity for these off grid households requires significant capital expenditure, to install a PV plus battery, with accompanying control equipment, as well as the hotplate and EPC. The eCook model sizes the equipment required to meet the cooking requirements of the household. The 100% eCook scenario requires 630 Wp of PV and a Lithium Iron Phosphate battery of 2.2 kWh. For 50% eCooking, these reduce substantially, to 220 Wp of PV and a 0.74 kWh battery, reflecting the high efficiency of the EPC. The financial analysis spreads these costs out over a 5 year period, and with a 10% (real) discount rate (equivalent to a 15% financing rate, given the current 5% inflation in Kenya) this leads to the monthly payments shown in Figure 45.

5.3 Environmental impact

Figure 46 shows the system diagram for case study 3 and Table 22 shows the scenarios considered.

Table 22 Description of options evaluated for SHS in Kenya

Scenario	**Devices**	**Quantity per household per day**	
100% Charcoal	Ceramic Jiko	1.75 kg charcoal	
100% LPG	2 Ring LPG burner	0.23 kg LPG	
100% Kerosene	Simple wick burner	0.25 kg kerosene	
100% Firewood	Three stone fire place	3.5kg firewood	
50% SHS, 50% Charcoal	SHS Ceramic Jiko sEPC (electric pressure cooker)	PV array, 1.32 m2 LFP Battery, 0.74 kW Inverter, <2.5 kW 0.87 kg charcoal	Efficiency of PV panels assumed to be 16%
50% SHS, 50% LPG	SHS 2 Ring LPG burner sEPC	PV array, 1.32 m2 LFP Battery, 0.74 kW Inverter, <2.5 kW 0.11 kg LPG	Efficiency of PV panels assumed to be 16%
50% SHS, 50% Kerosene	SHS Simple wick burner sEPC	PV array, 1.32 m2 LFP Battery, 0.74 kW Inverter, <2.5 kW 0.12 kg kerosene	Efficiency of PV panels assumed to be 16%
50% SHS, 50% Firewood	SHS Three stone fire place sEPC	PV array, 1.32 m2 LFP Battery, 0.74 kW Inverter, <2.5 kW 1.75kg firewood	Efficiency of PV panels assumed to be 16%
100% SHS	SHS sEPC Hotplate	PV array, 3.94 m2 LFP Battery 2.22 kW Inverter, 2.5 kW	Efficiency of PV panels assumed to be 16%

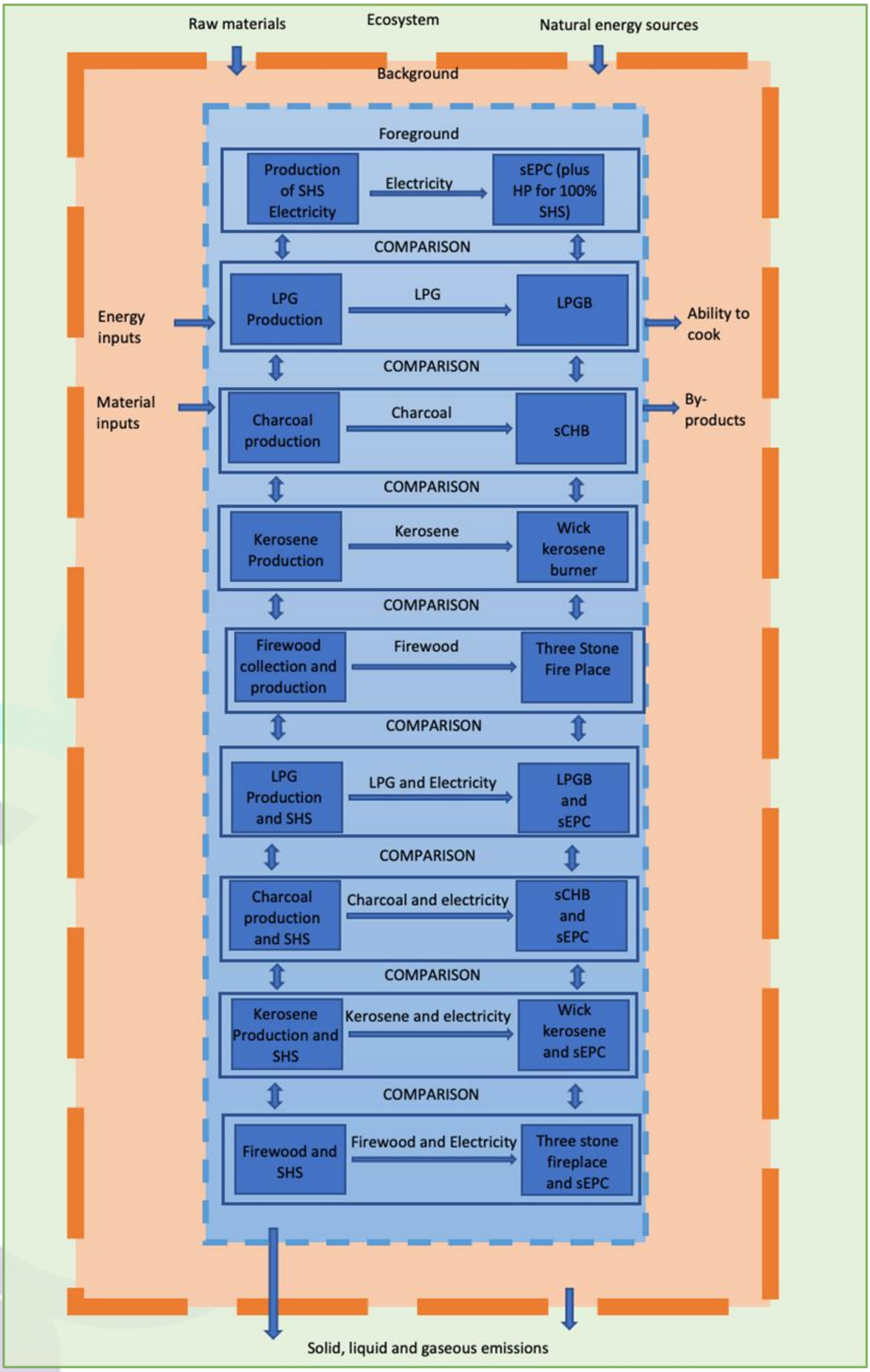


Figure 46 System diagram for SHS system in rural Kenya

Figure 47 shows the midpoint impact category results for each of the scenarios detailed in Table 22. It is clear from this that charcoal, either as 100% cooking or when combined with 50% SHS electric cooking, dominates almost all of the impact categories, followed by firewood cooking. The only category where this is not the case is human carcinogenic impact, where LPG dominates (as a result of the combination of chrome plated steel in the LPG burner (as seen for the Zambia and Tanzania case), and the impacts from SHS production), and Land use, where firewood dominates (from the land requires for sustainable forestry).

Looking at the impact categories of most relevance to MECS (Climate change, particulates, and human toxicity), the root causes for 100% cooking with charcoal and LPG are similar to those described for the Zambia case study in section 3.6, and for the use of firewood can be seen in the Tanzania case study in section 4.6. The main causes for the impacts from kerosene and the SHS system are given below.

For Climate Change:
- Similar to LPG, the main impacts result from kerosene combustion and production.
- For the SHS, the impacts are dominated by coal mining and electricity production in China. This is where the SHS systems are generally manufactured.

For particulate production:
- For kerosene, the impacts result from kerosene combustion (in the home) and gas flaring in petroleum processing systems.
- For the SHS system, copper mining and production dominate. Like Case Study 2 in Tanzania, copper is found in the SHS system in wiring and circuit boards.

For human carcinogenic toxicity:
- For kerosene, the impacts result from water discharge from petroleum/gas extraction, and sulphidic tailings from copper mining, associated with background systems that use copper in the production of kerosene (e.g. electrical systems in oil refining)
- For the SHS system, like particulate production, copper mining and production dominate, as copper is used in wiring and circuit boards.

For human non carcinogenic toxicity:
- For kerosene, the impacts arise from zinc in shredded vehicle remains, and sulphidic tailings. This comes from the background systems in the production of kerosene.
- For the SHS system, it is the treatment by landfill of slag from steel furnaces, and the treatment of redmud from bauxite digestion. The use of steel in supporting systems for PV pane production and aluminium in the frames for PV panels are the likely causes for these impacts.

Figure 48 shows the normalised midpoint categories (normalised against average annual (2010) per capita impact). As to be expected from the midpoint results, this shows that the impacts from toxicity issues are of greater concern, as these create a higher proportion of the total toxicity impacts from all sources.

Looking at endpoint impact indicators can show the effect of the midpoint categories on human health, ecosystems and resource use. At first glance from Figure 49, it would appear that resource use is the area where the greatest impacts occur, and that the SHS system shows the least impact for all three endpoint categories. Charcoal is noticeably worse, even when combined with the SHS.

When the SHS is combined with charcoal or firewood an approximately 50% improvement is delivered across all three endpoints. The benefits of the SHS system in combination with both the LPG and kerosene systems are less clear, for human health they appear to increase, for ecosystems they are reduced very slightly and for resources there is a clear improvement. Normalising the endpoint category results, shows that the human impact is of greatest concern (Figure 50).

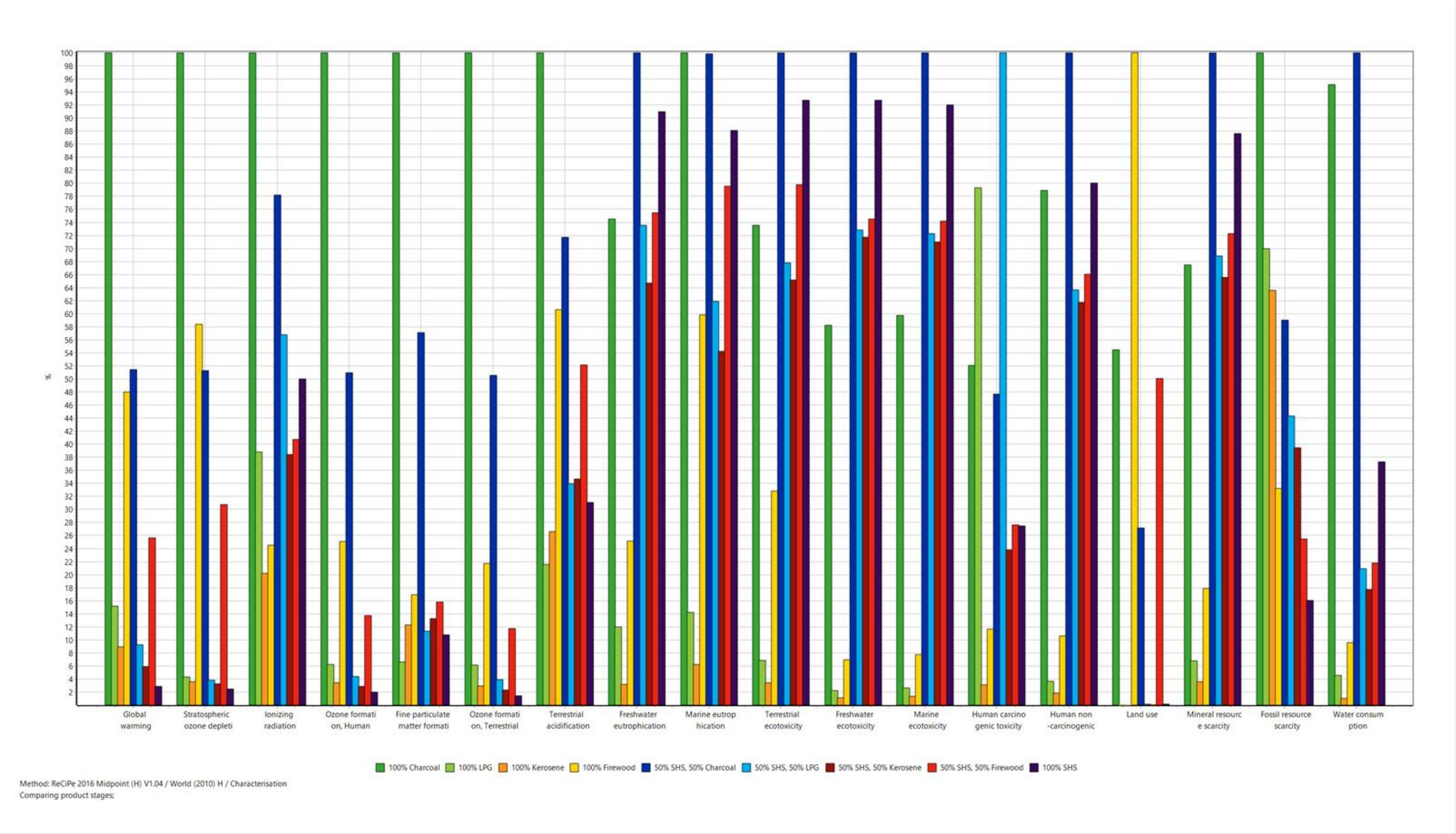


Figure 47 Midpoint impact categories for SHS system options in Kenya

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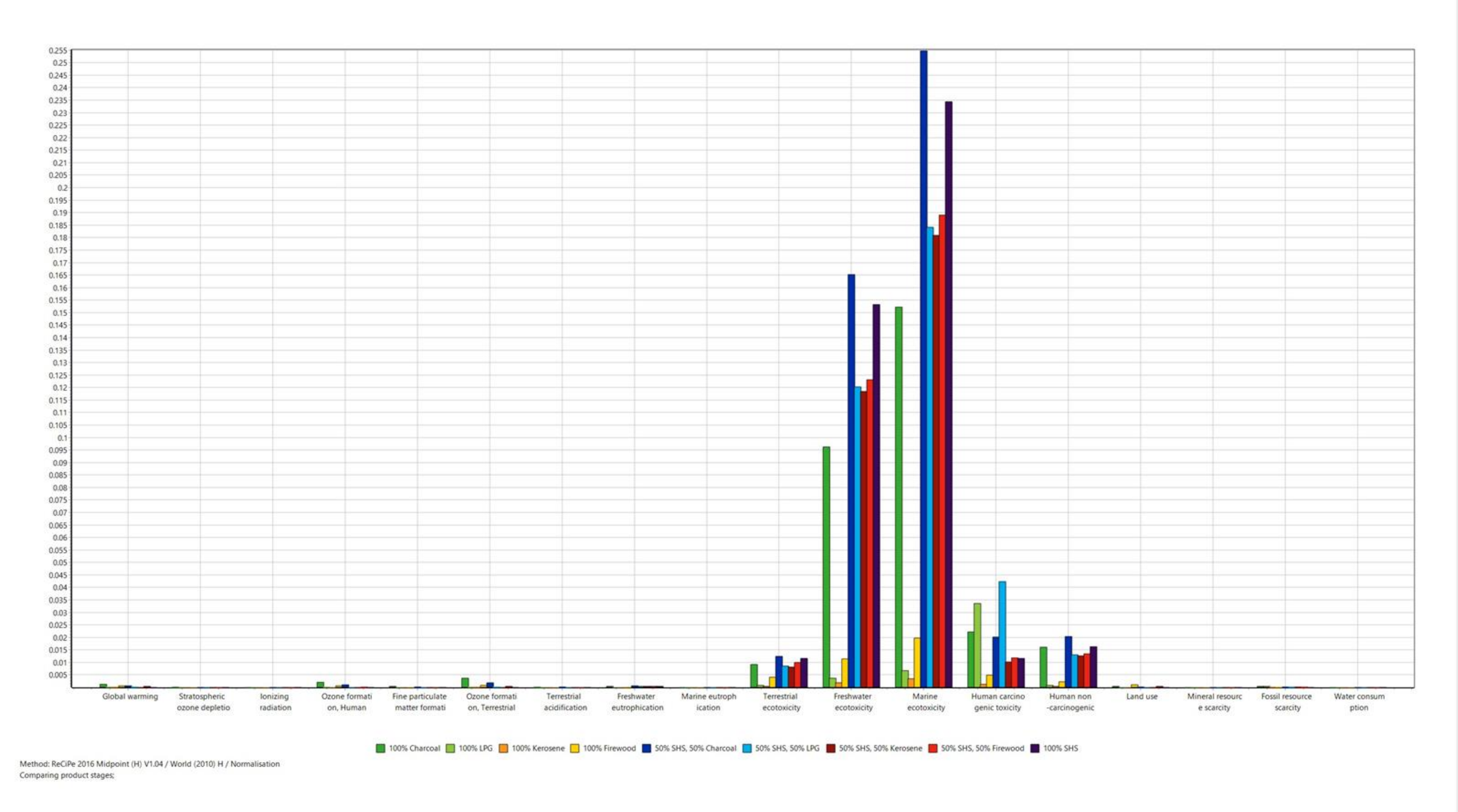


Method: ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H / Normalisation
Comparing product stages;

Figure 48 Normalised midpoint impact categories for SHS system options in Kenya

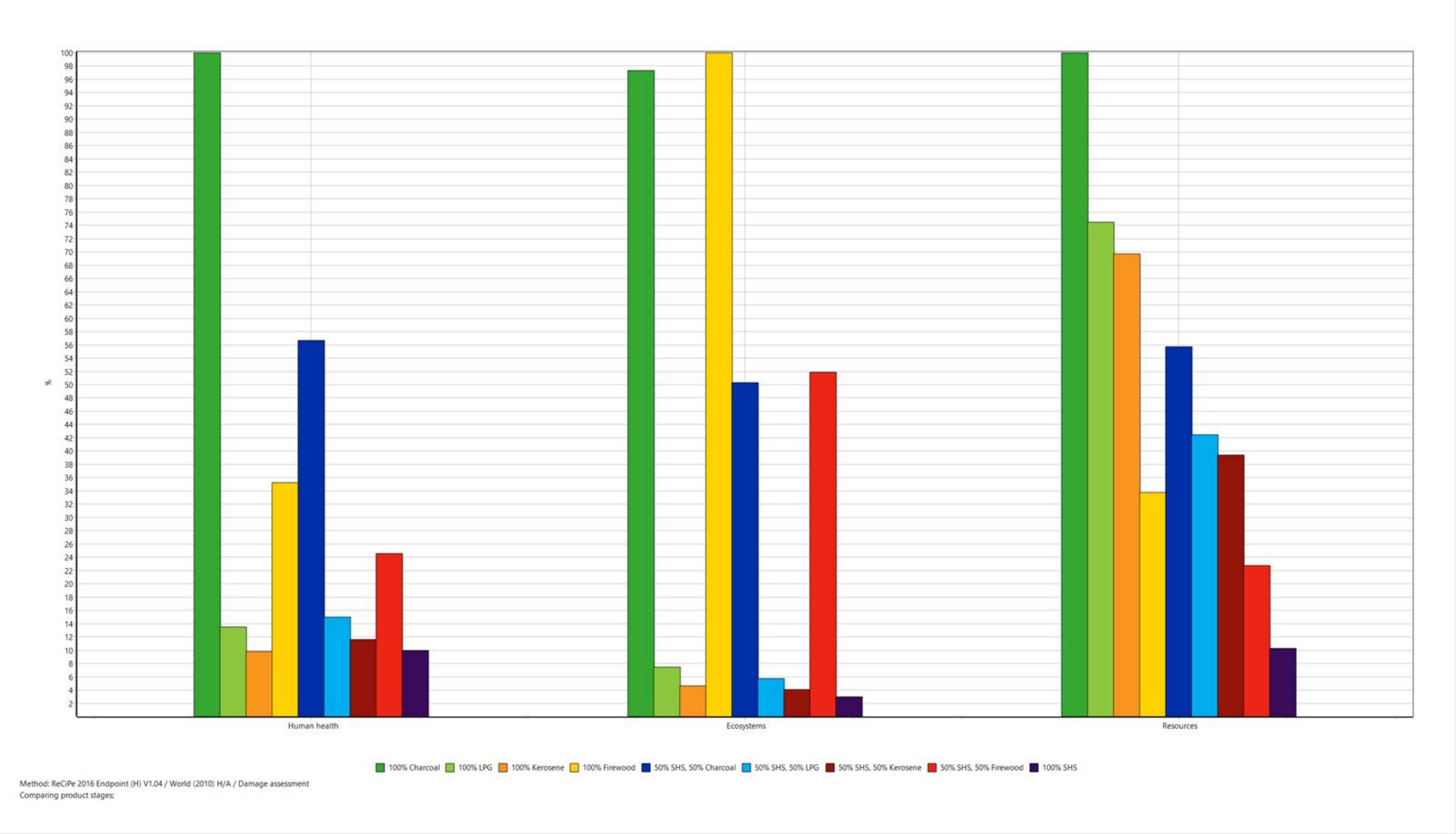


Figure 49 Damage to human health, ecosystems & resources for SHS options in Kenya

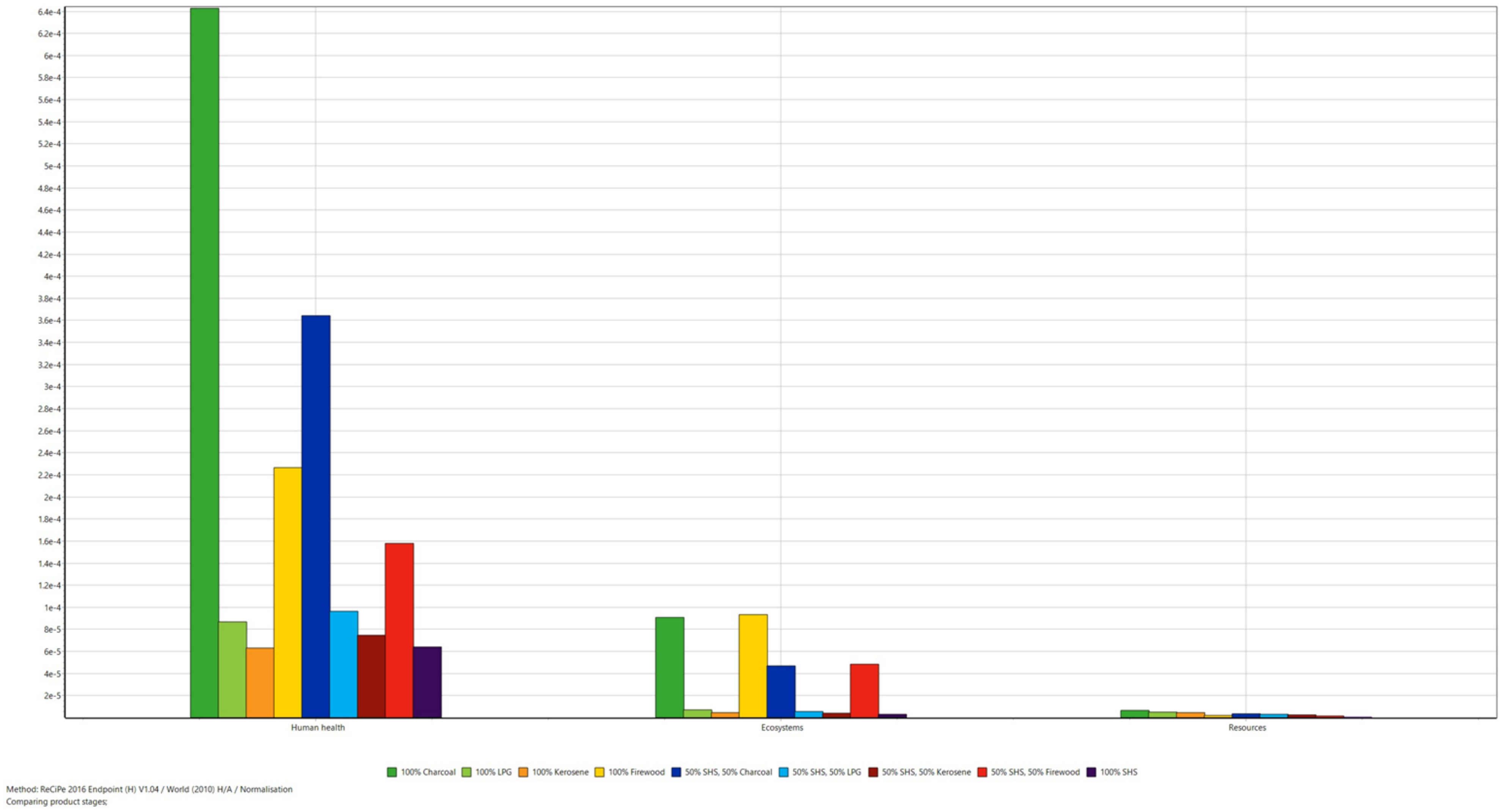


Figure 50 Normalised endpoint impact categories for SHS system options in Kenya

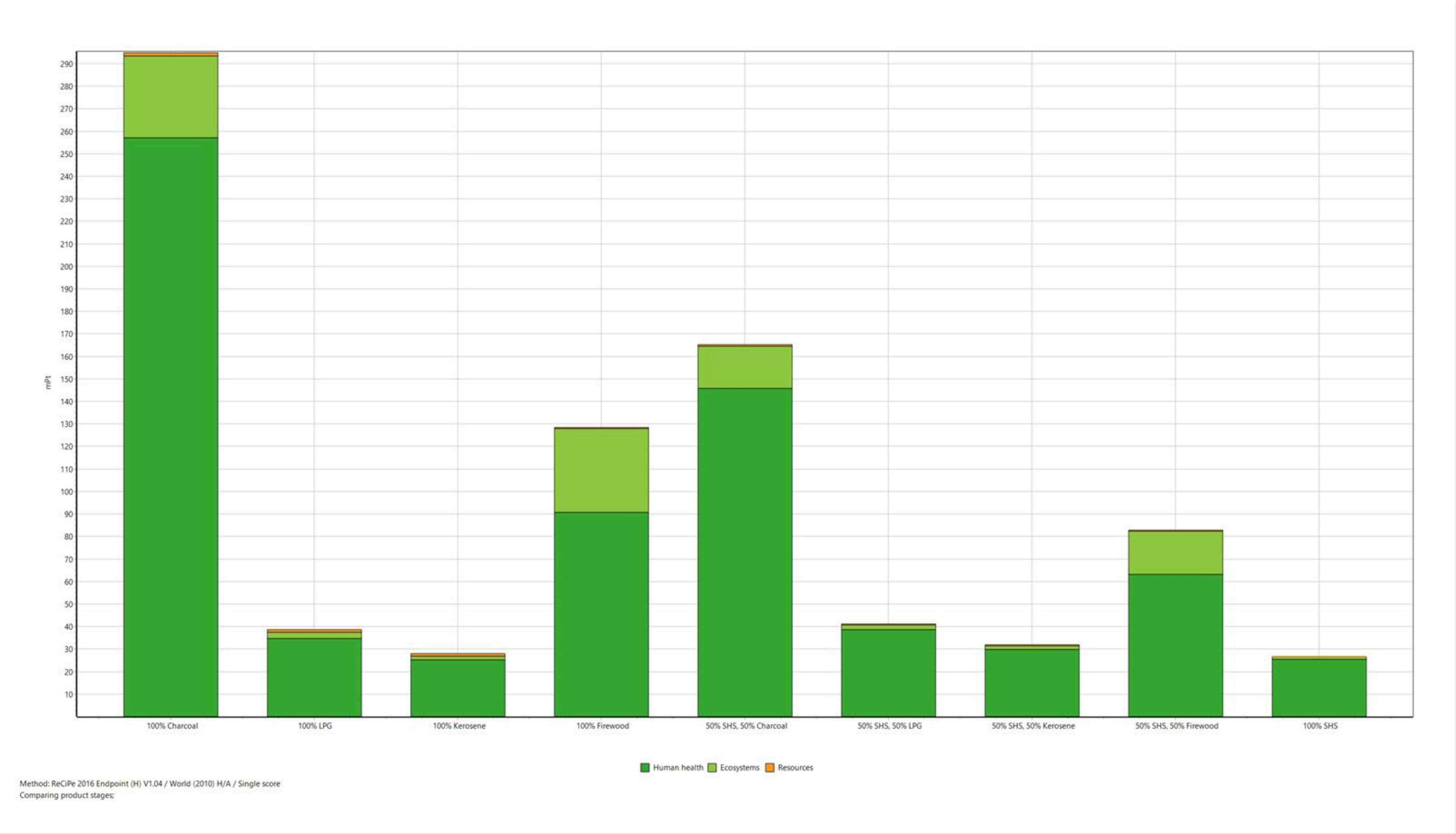


Figure 51 Aggregated single score endpoint impacts for cooking options for SHS in Kenya

Figure 51 shows a 'single score', aggregating the impact on human health, ecosystems, and resource use together. For those that normally cook with charcoal, the benefits of moving even partially to a SHS are clear and significant. This is also true for firewood, although the benefits are not as significant. The same however, cannot be said for those who currently use either LPG or kerosene. In both these cases, total impact increases very slightly as a result of moving to a mixed electrical and traditional fuel cooking set up. This is expected, given that the impacts from the SHS dominated at the midpoint category impacts for LPG and kerosene combined with SHS systems, whilst the impacts resulting from charcoal and firewood dominated when considering the mixed system. This would suggest the impacts associated with the full supply chain infrastructures and production for the SHS system are greater than that for either LPG or kerosene. The closeness of the results here are such that this result cannot be assumed with confidence, and finer granularity of the systems under review would be required to assess this more completely.

In order to identify the most effective modifications that cold be made to a SHS system in order to reduce its impact, and therefore make it a more attractive environmental option than LPG or kerosene, a contribution analysis was undertaken. Figure 52 shows the contributions of the main components of a SHS to the midpoint impact categories. This shows clearly that the PV and Inverter contribute the most impact, with the LFP battery contributing less. It should be recognised that the Inverter has been oversized in this example (2.5 kW). However, the working components between a 2.5 kW and a 1 kW inverter (the rating for many sEPC) does not vary significantly. In addition, there are likely to be other items that will be powered by the SHS (although for the purpose of this assessment it has been assumed that all the impacts associated with the SHS have been allocated to cooking).

Looking at the PV panels, inverter and battery in more detail, it is possible to identify the main causes for their impacts.

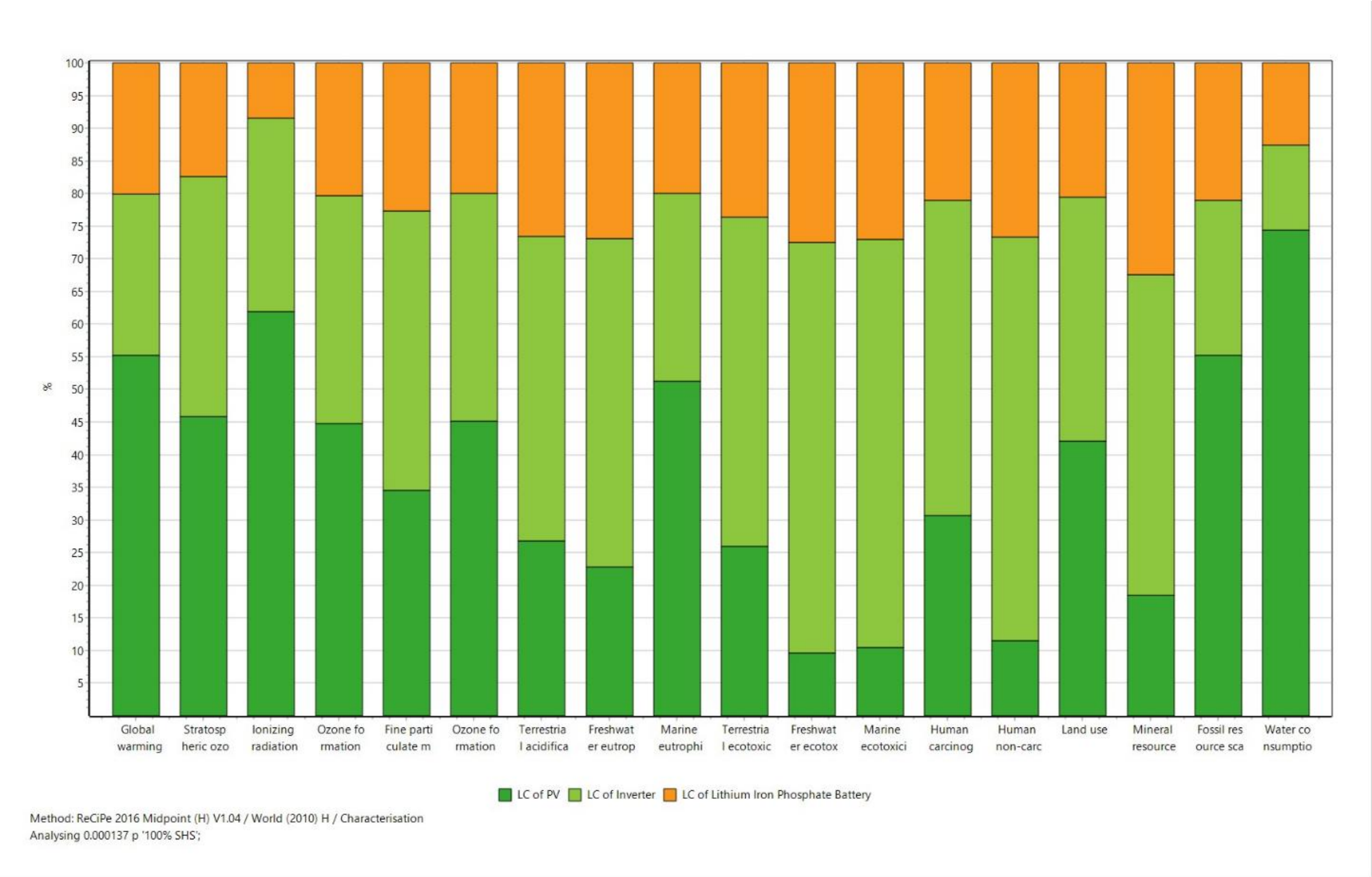
The PV panels contribute significantly to Global Warming Potential (GWP), ionising radiation, marine eutrophication and water consumption:

- For GWP, this comes from hard coal mining and the production of electricity generated by hard coal in China, where it is assumed the panels are produced.
- For Ionising radiation, this results from the tailings from uranium mining, again used for electricity production
- For marine eutrophication, the main causes are the treatment of wastewater from the PV production system, and the spoil from lignite mining.
- For water consumption, this is high because of the production of electronics grade silicon, for microprocessor chips.

The battery shows high impact on mineral resource use, fresh and marine ecotoxicity, terrestrial acidification and freshwater eutrophication:

- For freshwater, and marine toxicity, and freshwater eutrophication, the main activity of concern related either to the production of copper, or dealing with the sulphidic tailings that result from primary copper production.
- Freshwater eutrophication is also affected by the production of $LiFePO_4$
- Mineral resource consumption is highly affected by the use of lithium brine, this is unsurprising given the known scarcity of lithium.

For the inverter, the majority of the impact associated with this component are related to the mining and production of primary copper, through waste treatments for tailings, or the main copper production process itself. This is to be expected as the main component of an inverter is a circuit board.



Method: ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H / Characterisation
Analysing 0.000137 p '100% SHS';

Figure 52 Contributions of components of a SHS to midpoint environmental impact categories

5.3.1 Summary of environmental impacts

The key finding here is that a significant improvement in the environmental impact can be realised by moving away from charcoal or firewood to a SHS system, either partially or completely. For LPG and kerosene, it is not clear if any environmental benefits can be delivered in using a SHS system in preference for cooking. In order to improve the environmental performance of the SHS, and thus make it the more environmentally preferable choice, a contribution analysis was undertaken of its key components. The PV panels are one of the key contributors to the impacts associated with a SHS system (the other being the inverter). As for the mini-grid system, it is sensible therefore to consider what options exist to reduce the impact of the panels and inverters. The following points should be considered:

- Specifying the most efficient PV panels available and ensuring they are always operating as efficiently as possible, including regular cleaning to remove dust and other debris. As technology improves and new more efficient chemistries are developed, this will enhance the performance of PV SHS systems, and may make their use more advantageous when compared to LPG or kerosene.
- The current study does not consider End-of-life options. For items like the inverter, where there is potential for components to be re-used, this may reduce impact if a local recovery/repair and manufacturing service can be created to capture the value of these parts.
- The LFP batteries modelled here are considered manufactured from virgin materials. There is much research currently underway to evaluate the potential for reusing ‘spent’ LFP vehicle packs or their constituent cells which would have sufficient capacity for a second life (without recycling to components) for use in SHS[9].

The above are all local solutions which in combination, may reduce the environmental impact of SHS to a point where there is a clear benefit in a SHS over both kerosene and LPG. This analysis does not, of course, take into account reliability of supply of either kerosene or LPG, and since the increases in impact are marginal, this may be an acceptable offset to ensure cooking is always possible.

For the cooking devices, simple gas and kerosene stoves are more likely to be recovered and recycled through the informal economy, collected by scrap metal merchants and sold on for reprocessing. However, the EoL for PV panels and LFP batteries is a more complex process, and as yet, few recycling facilities exist in Kenya. Recycled components cannot easily be reconstituted back into to new PV panels or batteries, leading to a potential issue of what to do with the materials and/or components that are released from SHS systems.

Finally, these results are based on using a SHS sized for cooking only, and not providing any additional services, such as lighting, TV or charging of phones. In reality, a SHS system provides energy for much more than cooking, and the system boundaries would need to be expanded to take these other uses into account.

5.4 Case 3: summary findings

This third and final case explores the provision of eCooking for off-grid households in rural Kenya, through standalone solar PV plus battery power systems for each individual household, providing either 100% of the cooking or 50% through use of an EPC only, stacked with traditional fuels. The results reported are on the sizing of the system (e.g. the PV and batteries), the resulting costs and then the LCA for environmental impacts of that system, compared to cooking with traditional fuels. Key findings are:

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[9] MECS has supported pilot projects providing second life batteries for cooking: https://mecs.org.uk/wp-content/uploads/2020/12/MECS-TRIID-AMPERES-Final-Report.pdf

- With no form of existing grid supply of electricity available, introducing eCooking for this sort of region requires installation of a complete power supply, with the case study assessing individual Solar Home Systems. The system size required follows the eCooking scenario: 100% eCooking (assumed to require a hotplate and an EPC) needs PV of around 600 W and a Lithium Iron Phosphate battery pack of just over 2 kWh installed; these fall to 200 W of PV and a 0.75 kWh battery for the 50% eCooking case, reflecting the high efficiency of the EPC.

- Even with anticipated cost reductions for the equipment, such systems incur considerable upfront cost. However the eCook modelling of the financial investment shows that third party financing through some form of bespoke PayGo or leasing business model would result in monthly costs to the user that are competitive with charcoal.

- Of particular interest is the finding that a 'clean fuel stack' of the smaller eCook system stacked with LPG for the balance of cooking would cost a similar amount to cooking everything with LPG alone. This approach would reduce local emissions through substitution of renewable electricity for some of the LPG, and bring convenience benefits for the user, through the automatic controls in an EPC, as well as reduction in trips for refilling LPG cylinders. However the installation of any of these eCook systems would also bring valuable co-benefits, providing access to electricity for non-cooking services alongside the transition to eCooking.

- The Life Cycle Assessment shows the wider comparison between the different eCooking scenarios. When the impacts on human health, on ecosystems, and on resource use are aggregated, significant benefits are shown for SHS eCooking compared to use of charcoal and firewood. However, the aggregate impacts compared to LPG and Kerosene are similar. The SHS offers significant improvement n terms of resource use impacts, and perhaps marginal improvement for ecosystems, but in terms of human health effects the SHS impacts are on a par with those for LPG and Kerosene.

- The roots of the environmental impacts associated with the SHS are in production of all of the major electrical components: the PV, batteries and the inverter, although perhaps surprisingly the batteries have lowest impacts amongst the three. The human health impacts arise from all three supply chains, but the inverter production is particularly significant, driven by impacts from copper mining. As noted in the analysis, the inverter may well have been oversized. Also an inverter may not be needed, as DC powered EPCs are becoming commercially available.

- The environmental analysis shows clearly that the supply chain impacts of power electronics can be significant, and this suggests that accurate system design and sizing is important, and also that efforts to reduce impacts of eCooking (and off grid electricity access generally) should look closely at the materials and production processes used in the systems specified. Considerable efforts are underway to develop next generation solar PV and for alternative battery chemistries, in which efficiency and environmental impacts, alongside costs are key considerations. End-of-life options are not yet considered in the LCA, but local recovery/repair of devices, as well as material recycling may help mitigate some of the impacts.

In summary, this case study has shown that standalone PV-battery systems, akin to large solar home systems, could bring access to modern energy for cooking, as well as non-cooking services, to off-grid households. Where households are paying for traditional biomass cooking fuels, eCooking systems can bring financial savings and reductions in health, ecosystem and resource impacts. Cooking with LPG offers similar costs and a similar level of impacts, and a clean fuel stack combining an EPC with LPG could offer the household a range of attractive amenities.

6. Discussion and conclusions

The aims of this work were two-fold: firstly, to develop a mixed-methods approach for evaluating options for Modern Energy Cooking Services and secondly to explore a series of different energy access contexts using this wider framing, to both test and demonstrate the approach developed.

The typically separate areas of analysis and modelling that have been brought together are:

- Energy use and load patterns for electricity use for non-cooking energy services: implementing the Multi-Tier Framework characterisations of different household situations into a formal modelling tool.
- Energy use and load patterns for electricity use for cooking: implementing the evidence from cooking diaries into a formal modelling tool.
- Electric cooking system design, sizing and costing appliances and components.
- Analysis of the electricity distribution networks to which groups of households are connected, both pre-and post- transition to electric cooking, to define and quantify constraints.
- Life Cycle Assessment (from cradle to end of use) for the transition from traditional fuels to electric cooking, including appliances, fuels and electricity used and electricity supply infrastructure.

The opportunity was to utilise the growing body of detailed empirical knowledge about how people do – and would like to - cook, in a wide range of analysis types, allowing consistent exploration of technical, economic and environmental performance of eCook in different contexts. The challenge was to connect this knowledge, with all the variability and uncertainty therein, to different analysis techniques, each of which has their own data input requirements.

6.1 Findings from the case studies

In all three energy access contexts, the study found that eCook could offer: comparable or lower costs per month to users than use of traditional fuels; positive overall benefits in health, ecosystem and resource impacts; and with typical electricity supply infrastructures able to support transition of a significant number of households. eCook cost and environmental performances compare particularly favourably with use of charcoal.

The prospects were found to be particularly good in the grid-connected case for Zambia, partly due to the low tariffs for electricity making eCooking highly cost competitive but also because of low load factors within LV supply networks deployed in SSA, such that the existing network could support every household transitioning to electric cooking. For example, with around 80% of Zambian electricity coming from hydropower, the environmental impacts of eCooking were low.

Results show that adding eCooking loads roughly doubles household energy consumption among grid connected households (Case study 1). This illustrates a potential increase in revenue for utilities. The same effect can be seen in mini-grid applications but is more acute because of the relatively low level of non-cooking demand. This highlights an opportunity for mini-grid developers to consider systems designed to meet cooking loads. Increasing revenue is of particular importance for initiatives to increase grid access, which typically reach lower income households with lower levels of demand. Incorporating eCooking into energy access plans can, therefore, help improve return on investment by increasing demand.

The mini-grid case in Tanzania assumed relatively high tariffs that were in keeping with evidence from recent projects, but even so the predicted cost ranges for eCooking and for charcoal use show significant overlap. With charcoal costs expected to continue rising and eCook costs expected to fall, the benefits of eCook are likely to grow. Furthermore, according to World Bank projections (ESMAP, 2019) the tariff assumptions may well prove unreasonably high. From an environmental perspective, a switch away from charcoal to mini-grid eCooking showed substantial improvements in every impact category. With an initial transition to eCooking comprising an

EPC to cook 50% of the daily menu, the network analysis suggested around 10% of the households could be accommodated within the existing mini-grid capacity.

Comparing the environmental impacts associated with wood and charcoal consumption highlights the detrimental effects of cooking with charcoal. Aggregated figures indicate that charcoal can be over twice as harmful as wood as a cooking fuel. This needs to be more widely understood, as charcoal is typically the fuel of choice in urban areas, and rapid urbanisation suggests that charcoal consumption is set to increase, at least until clean alternatives are widely adopted.

For off-grid households in Kenya currently without any access to electricity and paying for their cooking fuels, introducing a large solar home system comprising PV, battery and EPC was shown to provide access to modern energy for cooking at competitive cost, as well as supporting non-cooking electricity services. Again, environmental benefits compared favourably to charcoal cooking across health, ecosystem and resource impact categories. Cooking with LPG offers similar costs and a similar level of impacts, and a clean fuel stack combining an EPC with LPG could offer the household a range of attractive amenities.

6.2 Benefits of the mixed-model approach

Considering eCooking using the mixed methods approach produces results that consider both a wide range of outcome types and the impacts on a wide range of stakeholder types. The network analysis shows what levels of eCooking are technically feasible in a given context. The eCook model shows how the costs of electric cooking would compare with the use of traditional fuels, and hence evaluates one important dimension of a household’s preferences. Implicit within the exploration of eCooking compared to traditional fuels is that households will benefit from reduction in indoor air pollution: the Life Cycle Assessment then provides a broader perspective to consider the full range of environmental impacts, at every stage of the supply chain, not just at point of use.

Expanding the environmental evaluation out from point of use to the full supply chain has provided important confirmation that electric cooking can offer environmental improvements compared to cooking with solid biomass, across each of grid, mini-grid and off-grid contexts. The production and supply chains of PV, batteries and associated electronics for the off-grid case give rise to some significant impacts, and the aggregate impacts on human health in particular are similar to those seen for LPG; however the eCooking impacts are lower than those for charcoal across the board.

Close attention to the timing of electricity use and cooking, grounded in empirical evidence on daily use, has supported detailed evaluation of the effects on electricity grids, revealing greater opportunities than otherwise evident. Diversity in how and when people cook, leads to expected aggregate peak loads from groups of households to be much lower than the total rated capacity of their appliances; the implications for the networks that supply them are profound: mini-grids should be able to support significant levels of Cooking, even with the relatively limited headroom typically seen in systems designed without cooking in mind and for main grids, the impacts of large scale eCooking may not be as serious as conventional wisdom dictates.

The LCA revealed relatively high impacts associated with some unexpected parts of the mini-grid supply chain, notably the chemical treatment on the distribution network supports. Linking the LCA to the network analysis brought the characteristics assumed for the network infrastructure into view, without which it is likely that the LCA would simply have adopted aggregate impact values for generic electricity supply. This linkage has also allowed exploration of the environmental performance of scenarios for increasing the capacity of the mini-grid to support wider use of eCooking, demonstrating that more complex hybrid solutions might be superior to simply increasing PV capacity.

Linking the LCA to the eCook design model allowed a thorough evaluation of possible fuel stacking strategies. The eCook model as used in ESMAP (2020) demonstrated that a 'clean fuel stack' of an EPC used for 'heavy' foods working with LPG used for other dishes could compete with LPG alone on cost to the user, and offer convenience benefits. LCA of those scenarios in the present study has shown no downsides from the full supply chain to such a fuel stack. The network analysis shows that such a '50% eCook' scenario permits a given network to support more households in transitioning to electric cooking, reducing the number of appliances each household needs to own and hence reducing the expected peak needs to own and hence reducing the expected aggregate peak load.

Combining the eCook design model with the LCA has also revealed that hotspots of environmental impact can occur in unlikely places: notably associated with inverters that might be used for an off-grid case. Pinpointing such issues can allow system designers to specify alternative products (e.g. DC EPCs), and to size devices carefully, avoiding unnecessarily high-capacity power electronics. Somewhat surprisingly, the LCA showed that use of a Lithium-Ion battery pack did not dominate in terms of any of the environmental impacts, with either the PV or the inverter showing greater effect in every one of the 15 impact categories.

6.3 Uncertainties and areas for further work

Each of the methods of analysis brought together here for the first time have an often complex and detailed set of requirements; as such bringing them together raises a number of questions and issues.

Sustainability analysis should balance economic, environmental and social dimensions. The present study has brought technical and economic analysis together with life cycle environmental assessment; as such the social perspective is not well represented. Several key social concerns are implicitly included, embedded within the very attention to MECS, and to underlying knowledge that has shaped the selection of scenarios and cases (such as the convenience benefits, primarily for women, observed in EPC trials). However a longer term ambition is to expand the LCA into a LifeCycle Sustainability Assessment (LCSA) that brings in social impacts, and economic impacts alongside the environmental performance. Policy and financing interests are pushing in this direction too, for example with broadly-based Results Based Financing mechanisms being trialled for cooking.

As noted earlier the LCA is currently looking at the 'cradle' to the end of the 'use' stage for devices and systems; it does not consider the options and impacts for 'end-of-life'. End-of-life for eCook appliances or systems is highly uncertain: there are few schemes in existence for managing waste electronics in sub-Saharan Africa for example. Neither is it clear what effect local repair and maintenance capabilities will have on the working lifetime of cooking system components, such as EPCs, inverters and so on. The volumes of PV and batteries reaching the end of life in their initial application are currently small, and so the pressure to establish effective schemes to take devices back, and to reuse or recycle them has not been great. There are opportunities to learn lessons from earlier moves in industrialised markets, and considerable entrepreneurial interest in innovations using circular economy principles to increase local manufacture and resource efficiency.

In cases where sufficient network and generation capacity exists, LV distribution networks have been shown to be able to cope at least in part with the addition of new electric cooking and other household loads. As the levels increase network problems will continue to rise, and perhaps be exacerbated (e.g. protection system disconnecting feeders) if left unmanaged. The ability to flexibly provide additional capacity in the system (either for LV network or mini-grid) at different times through the integration of distributed generation or energy storage becomes increasingly attractive. It is the use of *Active Network Management* and its equivalents that represents a more agile and 'cheaper' approach to supporting large scale eCook uptake beyond normal grid reinforcement.

The focus in this study has been on opportunities to grow the use of electric cooking, against an assumption of somewhat static demand for other electricity services: of course, demand for other uses of electricity is also likely to grow, whether through general increases in household affluence and appliance ownership, growth of productive uses locally, or introduction of other innovative uses for electricity, such as electric mobility. Cost comparisons demonstrate how widely held views that cooking with electricity is too expensive are now ill founded. Network analysis shows that cooking with electricity can increase consumer demand (and revenues) without necessarily requiring LV network strengthening. This work contributes to a strengthening view that electric cooking should, therefore, be a key part of efforts to tackle lack of access to MECS, but wider national and regional analysis is needed to fit cooking alongside other sectors in electricity system planning.

The detailed modelling of non-cooking and cooking loads across the day has allowed the diversity in household characteristics and user behaviours to be represented, and the aggregate effects of diversity on the loads seen by electricity networks has important implications for their ability to absorb additional eCooking. However this highlights the importance of the detail of the models and of the underpinning data. The existing evidence on household occupancy, on the timing of appliance use and even on the loads across typical appliance use cycles is not strong in sub-Saharan Africa, and many assumptions have been needed for this study. Further validation and refinement of those is needed, which should be helped over time by a growing number of pilot projects, supported by advances in monitoring equipment. The probabilistic simulation that forms the basis of the MECS household energy model is the appropriate way to handle uncertainties in the data, but further studies of the sensitivity of key conclusions could usefully be made.

The case studies were chosen to reflect the breadth of energy access contexts, but just three cases (with some scenario variants) cannot reflect the diversity of the real situations in which people live, cook and obtain energy. The cases and their results in this paper can only be illustrative examples; and specific results must be interpreted through attention to the assumptions underpinning the analysis. For example, the PV-Battery SHS for Kenya in the third case offers costs savings to households currently paying reasonably high prices for charcoal. Clearly this would not be the case for households who instead gather firewood: in that case there would be savings in fuel gathering labour/time, which might offer potential to increase productive activities, but the calculus is considerably more complex and contested. Alternative contexts, scenarios and assumptions can certainly be explored, but with considerable effort. The next step would be to work in partnership with one or more utility providers (grid, mini-grid, or SHS) to apply this approach to specific contexts, in which the input data assumptions can be replaced with more specific and accurate data.

The models for this study are ‘soft linked’ only, with data and assumptions shared from one model to the other, but with the model run independently, not ‘solved’ in a grand integrated simulation. Future developments to integrate some or all of the tools would simplify the analysis of other cases, and some sort of decision support tool is a long term aim. However even without bespoke analysis for a specific case, the results reported for the illustrative cases here offer useful guidance to find the greatest benefits and avoid the most significant impacts for electric cooking generally.

7. References

Bhatia, M. and Angelou, N. (2015) *Beyond Connections Energy Access Redefined. ESMAP Technical Report;008/15*. Available at: https://openknowledge.worldbank.org/bitstream/handle/10986/24368/Beyond0connect0d000technical0report.pdf?sequence=1&isAllowed=y.

Energydata.info (2020) *Zambia – Multi-Tier Framework Survey data*. Available at: https://energydata.info/dataset/zambia-multi-tier-framework-mtf-survey (Accessed: 1 March 2021).

EPRI (2021) *Simulation Tool – OpenDSS*. Available at: https://smartgrid.epri.com/SimulationTool.aspx (Accessed: 1 March 2021).

ESMAP (2019) *Mini Grids for Half a Billion People: Market Outlook and Handbook for Decision Makers*. Available at: https://openknowledge.worldbank.org/handle/10986/31926.

ESMAP (2020a) *Cooking with Electricity: A Cost Perspective*, *World Bank Group*. Available at: http://documents1.worldbank.org/curated/en/920661600750772102/pdf/Cooking-with-Electricity-A-Cost-Perspective.pdf.

ESMAP (2020b) *The State of Access to Modern Energy Cooking Services*. Energy Sector Management Assistance Program, The World Bank, Washington, DC. doi: 10.1596/34565.

ESMAP (no date) *Multi Tier Framework | Tracking progress toward sustainable energy goals*. Available at: https://mtfenergyaccess.esmap.org/ (Accessed: 1 January 2021).

Government of the Republic of Zambia (2009) *Rural electrification master plan for Zambia, 2008-2030 (2009 edition)*.

IEA (no date) *Access to electricity – SDG7: Data and Projections*. Available at: https://www.iea.org/reports/sdg7-data-and-projections/access-to-electricity (Accessed: 1 April 2021).

IEA IRENA UNSD World Bank & WHO (2020) 'SDG 7: Tracking The Energy Progress Report 2020'. Available at: https://trackingsdg7.esmap.org/data/files/download-documents/tracking_sdg_7_2020-full_report_-_web_0.pdf.

Leach, M., Leary, J., Scott, N., Batchelor, S., Chen, X., Ng, K.-S., Oduro, R. and Brown, E. (2019) *eCook Modelling*. Available at: https://mecs.org.uk/wp-content/uploads/2019/11/eCook-model-Working-Paper-November-2019.pdf.

Leach, M., Mullen, C. and Wade, N. (2020) *Household electricity load modelling: cooking and non-cooking*. Available at: https://mecs.org.uk/wp-content/uploads/2020/07/Household-load-modelling_working-paper_30_07_20.pdf.

Leary, J., Batchelor, S. and Scott, N. (2019) *Cooking Diaries 3.0 Protocols*. Available at: https://www.mecs.org.uk/wp-content/uploads/2020/12/Cooking-Diaries-3.0-Protocols-JL-9-9-19-LOW-RES.pdf.

Leary, J., Scott, N., Numi, A., Chepkurui, K., Hanlin, R., Chepkemoi, M., Batchelor, S., Leach, M. and Brown, E. (2019) *eCook Kenya Cooking Diaries*. Available at: https://www.mecs.org.uk/wp-content/uploads/2019/10/eCook-Kenya-Cooking-Diaries-September-2019-Working-Paper.pdf%0Ahttp://www.sussex.ac.uk/spru/research/projects/lct.

Leary, J., Scott, N., Sago, S., Minja, A., Batchelor, S., Chepkurui, K. and Sawe, E. (2019) *eCook Tanzania Cooking Diaries*. Available at: http://www.sussex.ac.uk/spru/research/projects/lct.

Leary, J., Scott, N., Serenje, N., Mwila, F. and Batchelor, S. (2019) *eCook Zambia Cooking Diaries – October 2019 Working Paper*. Available at: https://www.mecs.org.uk/wp-content/uploads/2019/10/eCook-Myanmar-

Cooking-Diaries-Working-Paper-13-10-19-JL-COMPRESSED.pdf.

Lombardi, F., Balderrama, S., Quoilin, S. and Colombo, E. (2019) 'Generating high-resolution multi-energy load profiles for remote areas with an open-source stochastic model', *Energy*, 177, pp. 433–444. doi: 10.1016/j.energy.2019.04.097.

Lombardi, F., Riva, F., Sacchi, M. and Colombo, E. (2019) 'Enabling combined access to electricity and clean cooking with PV-microgrids: new evidences from a high-resolution model of cooking loads', *Energy for Sustainable Development*, 49, pp. 78–88. doi: 10.1016/j.esd.2019.01.005.

Luzi, L., Lin, Y., Bonsuk Koo, B., Rysankova, D. and Portale, E. (2019) *Beyond Connections*, *Zambia. Beyond Connections. Energy Access Diagnostic Report Based on the Multi-Tier Framework*. doi: 10.1596/24368.

Mandelli, S., Merlo, M. and Colombo, E. (2016) 'Novel procedure to formulate load profiles for off-grid rural areas', *Energy for Sustainable Development*, 31, pp. 130–142. doi: 10.1016/j.esd.2016.01.005.

Monk, N. (2020) *An Investigation into the Functionality and Efficiency of an Electric Pressure Cooker Bought in Kenya Intended for the Domestic Market: 'Sayona PPS 6 litre'*. Available at: https://www.mecs.org.uk/wp-content/uploads/2019/12/Sayona-EPC-Description-and-Test-Results-V1.0.pdf.

Mullen, C. and Wade, N. (2020) *Appliance Data and Multi-Tier Framework for household electrical load modelling*. Available at: https://mecs.org.uk/wp-content/uploads/2020/12/Appliance-Data-and-Multi-Tier-Framework-_working-paper_201203_NOCOMMENTS-002.pdf.

Owen, A. (2016) *Policy Report on the Electricity Sector in Zambia*. Available at: http://www.freedomtocreate.com/ftc/wp-content/uploads/2017/06/FTC_Electricity_Sector_in_Zambia.pdf.

Powergen Renewable Energy (2020) *Accelerating uptake of electric cooking on AC microgrids through business and delivery model innovations*. MECS-TRIID Project Report, Version 1.3 - 21 February 2020. Available at: https://www.powergen-renewable-energy.com/ (Accessed: 16 March 2021).

Richardson, I., Thomson, M., Infield, D. and Clifford, C. (2010) 'Domestic electricity use: A high-resolution energy demand model', *Energy and Buildings*, 42(10), pp. 1878–1887. doi: 10.1016/j.enbuild.2010.05.023.

Rubin, E. S., Azevedo, I. M. L., Jaramillo, P. and Yeh, S. (2015) 'A review of learning rates for electricity supply technologies', *Energy Policy*, 86, pp. 198–218. doi: 10.1016/j.enpol.2015.06.011.

Schreiber, K. (2020) *Accelerating uptake of electric cooking on AC microgrids through business and delivery model innovations*. MECS-TRIID project report, Powergen Renewable Energy Ld, Ver 1.3, 21 February. Available at: https://mecs.org.uk/wp-content/uploads/2020/12/MECS-TRIID-PowerGen-Project-Report.pdf.

Soltowski, B., Galloway, S., Coley, W. and Strachan, S. (2020) *Impact of New Electric Cooking Appliances on the Low Voltage Distribution Network and Off-Grid Solar Microgrids Work has been conducted in support of the Modern Energy Cooking Services (MECS) Programme*.

Williams, N. J., Jaramillo, P., Cornell, B., Lyons-Galante, I. and Wynn, E. (2017) 'Load Characteristics of East African Microgrids. 2017 IEEE PES-IAS PowerAfrica Conference : 27-30 June 2017, Accra, Ghana', in. Institute of Electrical and Electronics Engineers.

Glossary

ABC	Aerial-Bundle Cable
AC	Alternating Current electricity
ADMD	After Diversity Maximum Demand
DC	Direct Current electricity
eCook	Electric cooking
EoL	End-of-Life
EPC	Electric Pressure Cooker
HH	Household
LCA	Life Cycle Assessment
LFP	Lithium iron phosphate battery (a type of Lithium-Ion battery)
LPG	Liquefied Petroleum Gas
LV, MV, HV	Low Voltage, Medium Voltage, High Voltage (electricity distribution)
MECS	Modern Energy Cooking Services programme, led by Loughborough University
mecs	Modern energy cooking services (as the goal)
mPt	Milli-Point (unit of Eco-Indicator in Life Cycle Assessment)
MTF	Multi-Tier Framework for energy access
PV	Photovoltaic solar power
SHS	Solar Home System
SSA	Sub-Saharan Africa
Wp	$\text{Watt}_{\text{peak}}$, unit of PV capacity