eCook Modelling

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Executive Summary

Electricity offers a route to clean cooking for many of the 3 billion people currently using biomass and solid fuels, as part of deepening access to modern energy.

In some places with historically low rates of electricity access, electricity generation is increasing and grid connection is expanding, and cooking with electricity may already be a viable proposition, although one often overlooked or assumed to be too expensive. However in many other places grid access remains low, or the grid supplies are unreliable or of poor quality. “eCook” is a potentially transformative battery-supported electric cooking concept designed to offer access to clean cooking and electricity to poorer households currently cooking on charcoal or other polluting fuels. Enabling affordable electric cooking sourced from renewable energy technologies could also provide households with sustainable, reliable, modern energy for a variety of other purposes.

This paper describes the eCook model, developed through a series of projects since 2015, together with the key assumptions and parameter values used in recent application studies. Summaries of the findings of those studies are provided here, along with links to papers with further detail.

There has been a widespread perception that electricity is too expensive for cooking in developing regions. Through detailed analysis of five diverse contexts, application of the eCook model shows that this is no longer true. With appropriate support, electric cooking will gain increasing commercial and political interest. Enabling the transition to eCooking will bring about environmental, gender and health benefits to some of the world’s most disadvantaged people.

The model is one of the tools deployed within the new Modern Energy Cooking Services (MECS) programme, supporting analysis of technologies and clean cooking applications. In parallel, a series of model developments are planned, allowing finer time resolution in the modelling, improved handling of uncertainties, and linkage to environmental and multi-criteria analysis frameworks being developed within MECS. The ongoing applications of the model, using data from pilot projects and other activities within MECS, will also strengthen the modelling.

The application and ongoing development of the eCook model will help build a more complete picture of the opportunities and challenges that await this emerging concept. Further outputs will be available from https://elstove.com/innovate-reports/ and https://www.mecs.org.uk/.

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Table of Contents

ACKNOWLEDGEMENT **2**

RIGHTS, PERMISSIONS & DISCLAIMER **2**

EXECUTIVE SUMMARY **3**

1 INTRODUCTION **6**

1.1 BACKGROUND 6

1.1.1 Context of the potential landscape change by eCook *6*

1.1.2 Introducing 'eCook' *7*

1.2 BACKGROUND TO THE ECOOK MODEL 8

2 ECOOK MODEL **9**

2.1 OUTLINE STRUCTURE 9

2.2 ENERGY USE IN COOKING 10

2.3 SOLAR 13

2.3.1 Solar insolation and PV output *13*

2.3.2 PV costs *16*

2.4 BATTERIES 18

2.4.1 Battery sizing *19*

2.4.2 Battery prices *21*

2.5 BALANCE OF SYSTEM 23

2.5.1 Battery charge controller *23*

2.5.2 Battery management system *25*

2.5.3 Inverter *26*

2.5.4 Additional balance of system *27*

2.6 COOKING APPLIANCES 27

2.7 COMPONENT LIFETIMES AND REPLACEMENTS 28

2.8 BUSINESS MODELS AND INVESTMENT FINANCING 29

2.9 FUEL/APPLIANCE STACKING 30

2.10 TREATMENT OF UNCERTAINTY 31

2.10.1 Different or varying household cooking needs and practices *31*

2.10.2 Uncertainty in appropriate values for parameters *32*

2.10.3 Different financing assumptions *34*

2.10.4 Changes in parameter values over time *34*

2.11 MODEL IMPLEMENTATION 34

3 APPLICATIONS **36**

3.1 DFID PEAKS, 2015 36

3.2 INNOVATE UK 36

3.2.1 Modelling eCook in Myanmar – inputs to a participatory cooking workshop *37*

3.2.2 Modelling eCook in Tanzania: input to the national stakeholders solar electric cooking workshop *38*

3.3 MECS-ESMAP REPORT 39

3.3.1 Overview of methodology and cases *39*

3.3.2 Cooking loads *42*

3.3.3 Technology performance and cost assumptions *44*

This research was funded by DfID/UK Aid and Gamos through the Innovate UK Energy Catalyst and the MECS programme

3.3.4 Summary of results 45
3.3.5 Overall conclusions on MECS/ESMAP modelling 52

4 CONCLUSIONS 53

5 REFERENCES 54

6 APPENDIX 56

6.1 APPENDIX A: PROBLEM STATEMENT AND BACKGROUND TO INNOVATE ECOOK PROJECT 56
6.1.1 Beyond business as usual 56
6.1.2 Building on previous research 58

6.2 SUMMARY OF RELATED PROJECTS 61

6.3 ABOUT THE MODERN ENERGY COOKING SERVICES (MECS) PROGRAMME. 62

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1 Introduction

The aim of this working paper is to set out the structure and details of the eCook model, together with the key assumptions and parameter values used in recent application studies.

In particular, the paper refers to studies undertaken for a broader project in 2018 designed to assess the opportunities and challenges that lay ahead for eCook in high impact potential markets, funded by Innovate UK's Energy Catalyst Round 4 by DfID UK Aid and Gamos Ltd. (https://elstove.com/innovate-reports/).

A much deeper analysis of the data collected during the Innovate project, as well as ongoing development of the eCook model, has been supported by the Modern Energy Cooking Services (MECS) programme (Batchelor et al, 2019). The model has now been used to support the development of the 2019 MECS-ESMAP report on electric cooking. The core model is the same for both applications, but some differing assumptions have been made, detailed in the respective sections of this paper.

The overall aims of the Innovate project, plus the series of interrelated projects that preceded it and the MECS programme are summarised in the Appendix.

1.1 Background

1.1.1 Context of the potential landscape change by eCook

The use of biomass and solid fuels for cooking is the everyday experience of nearly 3 billion people. This pervasive use of solid fuels and traditional cookstoves results in high levels of household air pollution with serious health impacts; extensive daily drudgery required to collect fuels, light and tend fires; and environmental degradation. Where households seek to use 'clean' fuels, they are often hindered by lack of access to affordable and reliable electricity and/or LPG. The enduring problem of biomass cooking is discussed further in *Appendix A: Problem statement and background to Innovate eCook project*, which not only describes the scale of the problem, but also how changes in renewable energy technology and energy storage open up new possibilities for addressing it.

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1.1.2 Introducing 'eCook'

eCook is a potentially transformative battery-supported electric cooking concept designed to offer access to clean cooking and electricity to poorer households currently cooking on charcoal or other polluting fuels (Batchelor, 2013, 2015a, 2015b). Enabling affordable electric cooking sourced from renewable energy technologies could also provide households with sustainable, reliable, modern energy for a variety of other purposes.

A series of initial feasibility studies were funded by DfID UK AID under the PEAKS mechanism (available from https://elstove.com/dfid-uk-aid-reports/). Slade (2015) investigated the technical viability of the proposition, highlighting the need for further work defining the performance of various battery chemistries under high discharge and elevated temperature. Leach & Oduro (2015) constructed a techno-economic model, breaking down the eCook concept into its component parts and tracking key price trends, concluding that by 2020, monthly repayments on PV-eCook were likely to be comparable with the cost of cooking on charcoal. Brown et al (2017) review behavioural change challenges and highlight two distinct opportunities, which open up very different markets for eCook:

- PV-eCook uses a PV array, charge controller and battery in a comparable configuration to the popular Solar Home System (SHS) and is best matched with rural, off-grid contexts.
- Grid-eCook uses a mains-fed AC charger and battery to create distributed household electricity storage for cooking using electricity sourced from unreliable or unbalanced grids, and is expected to best meet the needs of people living in urban slums or peri-urban areas at the fringes of the grid (or on a mini-grid) where blackouts are common an/or loads are constrained.

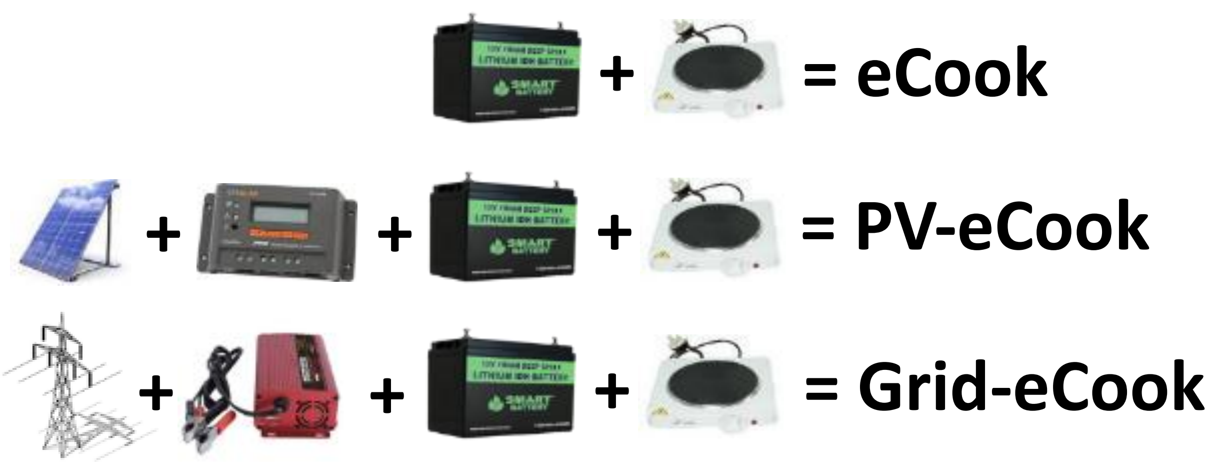

Figure 1: Pictorial definitions of 'eCook' terminology used in this report.

1.2 Background to the eCook model

The eCook model comprises numerical simulation of the cooking undertaken by a household and the energy required for that, linked to a system design model for an eCook device, either standalone (solar-battery-eCook) or grid connected (grid-battery-eCook). The overall aim is to be able to compare the costs of cooking with eCook with a baseline alternative (eg cooking with charcoal or LPG).

The initial model development for eCook was undertaken for a consultancy to the UK's Department for International Development in 2015. This was a simple 'proof of concept' simulation, characterising the technologies and the cooking energy requirements, based on secondary data and only including a single electric cooking appliance, the hotplate. That work is unpublished in the academic literature but is available in Leach and Oduro (2015). Promising results from that work supported the case for funding to Innovate UK's Energy Catalyst Round 4.

The model was further developed and refined through implementation with new empirical data on cooking practices and fuel use gathered in other parts of the Innovative study, undertaken through 2018. The model has then been applied, with updates of key parameter values (eg battery costs), for the MECS-ESMAP report on electric cooking (forthcoming), exploring a wide range of different implementations of electric cooking stacked with other fuels.

The underlying model is being further extended within the ongoing MECS programme, introducing finer time resolution for analysis of cooking energy use and the supply needed from eCook devices, and adding probabilistic simulation of parameter value uncertainty. Applications of the model will continue throughout MECS, as and when useful to support technical developments or for application studies.

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2 eCook model

2.1 Outline structure

The model is designed to explore alternative ways to deliver the 'cooking service' currently delivered by traditional stoves and fuels; as such, the important metric is not cost per unit of electricity delivered from an eCook system, but is related to the cost per meal.

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, and an empirically-based model for battery degradation, capturing the high current drain and harsh operating conditions for this application.

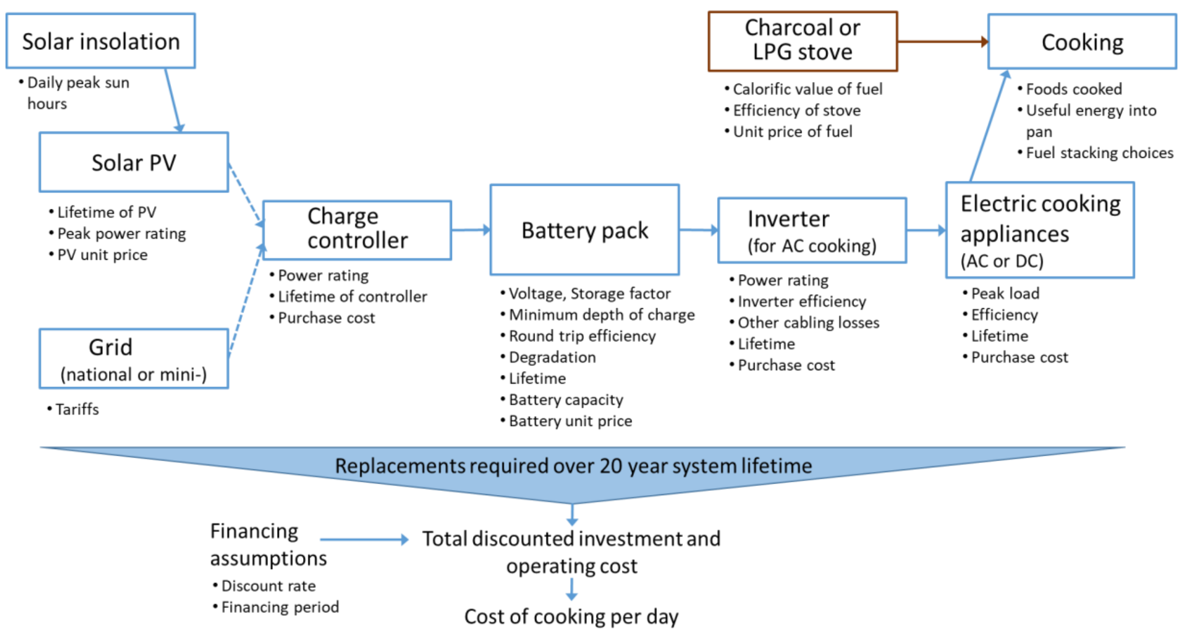

Figure 2 eCook model schematic, showing key parameters

The energy needs for cooking define the requirements of one or more electric cooking appliances and a matching inverter (if appliance uses AC). The eCook system is sized to meet a user-defined fraction of this total cooking demand, with the balance met from a specified traditional fuel.

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. Alternatively, for an on-grid or on-minigrid application, the load on the grid is calculated. The battery, solar PV (if used) and balance of plant are sized for daily load balancing. A user-defined factor is

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included 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 running flat. 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. Financing assumptions follow the business model to be represented, with the final result being comparison of the costs of cooking per day between the eCook system and a baseline of traditional fuel purchases.

2.2 Energy use in cooking

The eCook modelling embraces both characterisation of the electricity and/or fuels needed for cooking and of an eCook system to deliver that. Essentially the link between the two parts could be a single number, representing the electricity needed to meet the daily cooking requirements. This section provides an overview of recent research into cooking practices and energy use, and key results for fuel and electricity demands that have been used in the eCook design modelling. Further detail on the methods used for cooking research, and statistical analysis of results for each country, can be found in the country cooking diary reports in the MECS Working Papers, at https://www.mecs.org.uk/working-papers/.

The literature on what and how people cook is remarkably sparse. Ravindranath and Ramakrishna (1997) sought to determine the relative efficiencies of different stove and fuel types. They undertook standardised water boiling tests to determine the basic heat transfer efficiencies, and controlled food cooking tests of fuel use for standard meals. They concluded there were similar relative efficiencies shown in both tests, with heat transfer efficiency ranging from 15% for firewood on a traditional three stone fire and 23% for traditional use of charcoal to 60% for LPG and 71% for an electric hotplate. Their cooking tests show fuel use per kg food cooked, with similar distribution by fuel and stove type; but the study did not look at a range of typical meals cooked, or at the variety of real cooking practices. In a study in South Africa, Cowan (2008) undertook similar laboratory tests, but also studied energy use by 80 real households cooking a wide range of foods and meal types. A typical meal of rice and chicken stew for four people used 0.71kWh on an electric hotplate, 1.09kWh with LPG and 1.32kWh with Kerosene. The study provides a rich dataset of energy use by meal type, however in the study locations of peri-urban South Africa there was almost no use of biomass fuels..

The cooking diary studies were designed to offer a deeper exploration into the unique cooking practices of individual households, paired with quantitative measurements of energy consumption. It is usually

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easier to control heat levels with modern fuels such as gas & electricity than biomass, as they can be turned up/down and on/off in an instant. There is also a wide range of electric cooking appliances, each designed for specific processes (e.g. kettles for heating water). Therefore, it is important to know how often people need to fry, boil, reheat or use other cooking methods.

Cooking diaries are a novel methodology to address the lack of data around how people currently cook with biomass and how they might cook with electricity. Cooking is a deeply culturally-embedded practice, therefore understanding the nuances around how the intended beneficiaries of a clean cooking intervention actually cook is critical. Data on cooking practices, fuel/electricity use and user experience were collected in each of four countries. Focus groups offered a deeper qualitative exploration of how people currently cook, how they aspire to cook in the future and the compatibility of these cooking practices with the strengths and weaknesses of cooking on battery-supported electrical appliances.

This mixed methods approach gathered data from cooking diary forms (foods cooked, cooking processes/times, appliances used), energy measurements (weighing fuels and plug-in kWh meters), registration surveys (simple demographic data) and exit surveys (qualitative user experience feedback & observational eCooking Challenges). In each country studied to date, 20 households recorded data in two stages:

- *Phase 1 Baseline (2 weeks)*: cooking as normal, simply recording data.
- *Phase 2 Transition (4 weeks)*: cooking with electric appliances only.
- 

Figure 3: An enumerator training a participant to record data during the cooking diaries in Nairobi, Kenya. The electric cooking appliances are plugged into an energy meter in the top right of the photo.

Energy consumption when using a single fuel was compared on different bases: all events, daily consumption and averages of main heating events (breakfast, lunch and dinner). Energy consumption

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ratios were calculated for each set of results by dividing the energy consumption when using non-electric fuels by the equivalent consumption when using electricity. Ratios calculated for individual meals show a high degree of variance, as sub-sample sizes were small and energy consumption for specific foods is highly sensitive to appliance e.g. Electric Pressure Cookers (EPCs) use 80% less energy than hotplates for heavy foods. However the figures show remarkable consistency across different measures, suggesting the energy ratio for charcoal is around 10, i.e. cooking with electricity uses roughly 10% of the energy used to cook with charcoal.

Figure 5 and Figure 5 illustrate the efficiency advantage seen for electric cooking, with data plotted by food cooked and by meal type respectively.

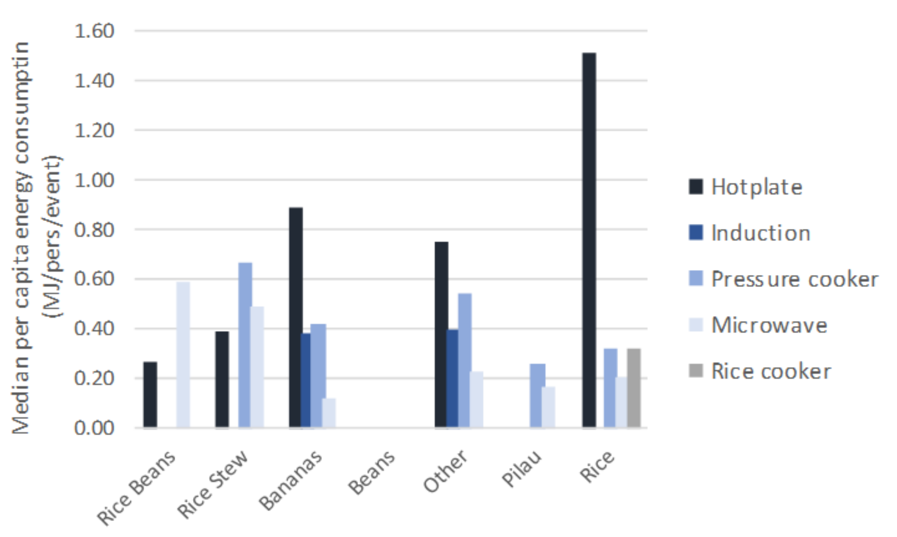

Figure 4 Specific energy consumptions of different electrical cooking appliances (n>=5)

Unlike biomass stoves, which waste significant amounts of energy during lighting and after cooking has finished, electric stoves can be turned on and off in an instant. What is more, advanced electric cooking appliances such as EPCs also use insulation, pressurisation and automatic control to prevent heat from escaping from the cooking pot, speed up cooking and precisely maintain the temperature in the pot.

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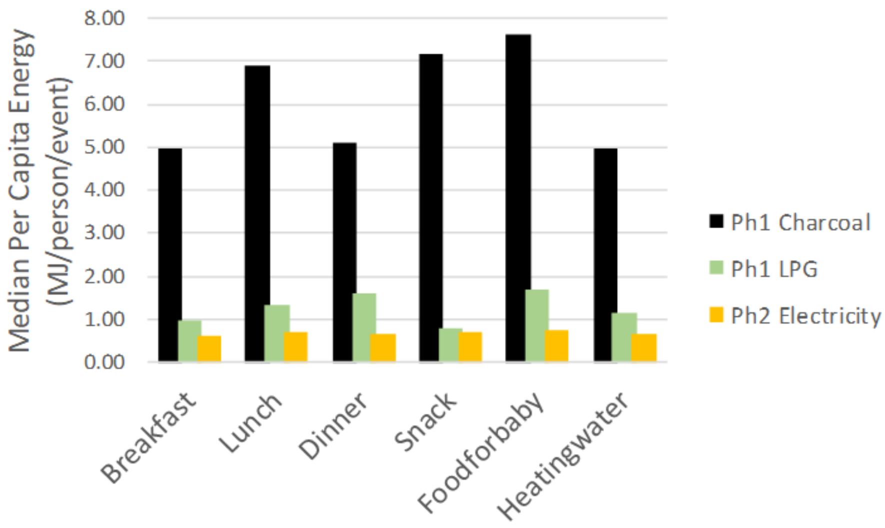

Figure 5 Per capita energy consumptions for different heating events

The research showed considerable variation in total household cooking energy use across the four countries within the Baseline and Transition periods. A key source of variation in energy use was found to be the cook's practices, including specific efficiency measures. For example putting a lid on a pan will save fuel and hence cost, but may interfere with a cook's wish to stir the pot.

The data collected during the cooking diary studies are extensive, and can be analysed in different ways (eg per dish, per meal, per household) dependent on the use to be made of it. Further details are in the set of MECS Working Papers for each country, available at https://www.mecs.org.uk/working-papers/. One specific analysis is presented in section 3.3.2 for application of the model in the MECS/ESMAP report. Further analysis, to look at the foods cooked and the timing of those activities, is planned as part of the next stages of the eCook model development within the MECS programme.

2.3 Solar

2.3.1 Solar insolation and PV output

The power output of a PV module depends primarily on the incident solar radiation (the 'irradiance') and the operating temperature. Manufacturers report rated (or 'nominal peak power') output in Watts produced under standard test conditions of 1000W irradiance per square meter of panel area (directly incident and with standard spectrum of light) and at 25degC (IEC, 2016). The effects of lower light intensity and of different operating temperatures vary between different PV materials, however most show decreased efficiency at lower light intensity and at higher temperatures. Additionally, the angles of alignment of the panel to the sun (the inclination angle, measured from the horizontal plane and the orientation angle, relative to due South in the Northern Hemisphere, or to due North in the Southern) change the effective insolation. The concept of PV 'efficiency' is thus highly dependent on conditions, and a single parameter value is rarely used in system calculations, with the focus instead on combining a characterisation of PV performance under different conditions with assumptions about the expected operating conditions.

In terms of irradiance, the solar intensity in any particular location varies with latitude and longitude, with season as well as with local weather. The job of the PV system in this application is to deliver sufficient electricity each day to recharge the batteries such that they are able to deliver the required electricity for cooking. A full system sizing should take a probabilistic approach, looking at the expected range of electricity output each day, and the impacts of that, via a dynamic model of the whole system that can look at the charge-discharge patterns from one day to the next. For the present model, we take a simpler approach considering just one day, estimating the average daily electricity output per kWpeak and sizing the PV panels such that this average output is sufficient to recharge the batteries that day. However, as in the battery section, we then add a factor to explore the cost of increasing battery capacity such that it can 'ride through' one or more days of low PV output, delivering the cooking service without running out before it is recharged.

There is one further parameter though needed for the PV sizing. Whilst a fully dynamic model is beyond the scope of this study, it is essential to consider seasonal variation in irradiance, as additional battery capacity cannot help smooth out month by month changes in PV output. Any location sees irradiance reduce for winter or monsoon months, and rise for summer or dry seasons. The PV-Battery cooking system can thus be sized in different ways: with a larger PV to operate year round as the principal means of cooking, or with a smaller PV, capable of producing sufficient energy each day in sunnier periods. The latter might work perfectly well for some households happy to fuel stack. However, whilst a smaller system would be cheaper, the capital cost of the system is shared out over fewer days, and thus the overall impact on the affordability of the system is uncertain. In some locations the variation in irradiance can be large: easily a factor of two, and thus the choice between a small or large system might be important. However in many places in Africa the variation is much smaller. The present model defaults to sizing the system such that it should operate year-round, and explores alternatives in sensitivity analysis. The model also calculates the likely 'surplus' electricity stored in the battery each day during sunnier periods, which will be available for other electricity end-uses as a co-benefit.

The EU's PVGIS project (Šúri et al, 2005) provides an online tool to estimate PV electricity generation (per 1kW peak or rated output), with user choices for key parameters as above (but with typical values

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available as defaults) and with user selection of the location of the system. This combines a detailed model of irradiance by location with characterisations of PV performance and of wider system losses. For the present model we use the PVGIS tool to produce estimates of PV output, varying key parameters. The main result taken is the average daily electricity output per kWpeak: we take the average value for the month with the lowest output (to size the system to operate year-round), as highlighted in the two example tables below.

(1) Location: 0°18'22" South, 36°4'44" East, Elevation: 1804 m a.s.l., (Nakuru, Kenya)

Solar radiation database used: PVGIS-CMSAF
Nominal power of the PV system: 1.0 kW (crystalline silicon)
Estimated losses due to temperature and low irradiance: 12.7% (using local ambient temperature)
Estimated loss due to angular reflectance: 2.7%
Other losses (cables, inverter etc.): 0.0%
Combined PV system losses: 15.0%

Fixed system: inclination=1°, orientation=-155°				
Month	**E_d**	**E_m**	**H_d**	**H_m**
Jan	5.44	169	6.44	200
Feb	5.66	158	6.78	190
Mar	5.65	175	6.77	210
Apr	4.98	149	5.91	177
May	5.17	160	6.07	188
Jun	5.05	152	5.89	177
Jul	4.92	152	5.74	178
Aug	5.14	159	6.02	186
Sep	5.31	159	6.28	188
Oct	5.10	158	6.06	188
Nov	4.69	141	5.54	166
Dec	5.04	156	5.95	184
Yearly average	**5.18**	**157**	**6.12**	**186**
Total for year		**1890**		**2230**

(1) Location: 7°16'59" South, 36°21'0" East, Elevation: 583 m a.s.l., (Dodoma, Tanzania)

Solar radiation database used: PVGIS-CMSAF
Nominal power of the PV system: 1.0 kW (crystalline silicon)
Estimated losses due to temperature and low irradiance: 14.8% (using local ambient temperature)
Estimated loss due to angular reflectance: 2.6%
Other losses (cables, inverter etc.): 0.0%
Combined PV system losses: 17.0%

Fixed system: inclination=8°, orientation=-172°				
Month	**E_d**	**E_m**	**H_d**	**H_m**
Jan	4.80	149	5.82	180
Feb	4.83	135	5.91	166
Mar	5.46	169	6.65	206
Apr	4.86	146	5.87	176
May	4.82	149	5.77	179
Jun	5.01	150	5.94	178
Jul	5.07	157	6.03	187
Aug	5.37	166	6.45	200
Sep	5.87	176	7.13	214
Oct	6.04	187	7.39	229
Nov	5.58	167	6.85	206
Dec	4.95	153	6.02	187
Yearly average	**5.22**	**159**	**6.32**	**192**
Total for year		**1910**		**2310**

Ed: Average daily electricity production from the given system (kWh)
Em: Average monthly electricity production from the given system (kWh)
Hd: Average daily sum of global irradiation per sq.meter received by the modules (kWh/m2)
Hm: Average monthly sum of global irradiation per sq.meter received by the modules (kWh/m2)

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The solar PV is sized as follows:

$$C_{pv} = \frac{E_{discharge}/E_{d,min}}{\eta_{battery}} \times (1 + F_{PV\ decay}) \times (1 + F_{PV\ oversize})$$

C_{PV}: Capacity of PV (kWp)

$E_{discharge}$: Daily battery discharge required (kWh/day)

$E_{d,min}$: Average daily electricity production in the least sunny month (kWh/kWp/day)

$\eta_{battery}$: Battery roundtrip efficiency (%)

$F_{PV\ decay}$: PV performance decay factor (% over lifetime)

$F_{PV\ oversize}$: Uprating factor to match battery oversize (%)

2.3.2 PV costs

Solar PV has been in use in developing countries for many years, both for larger scale installations but also at household scale, notably for Solar Home Systems, of a few tens of watts. A solar PV system can be described as a set of PV modules, comprising of individual solar cells held in some form of casing, and the Balance of system (BOS) comprising wiring, installation equipment and any inverter needed. For most PV systems, such as residential power or utility scale solar farms, there is also a significant installation cost. However for the current application the installation costs should be low.

PV cost projections are derived from historic data on module prices (IRENA, 2018), demonstrating current prices of around USD0.4/kWh. Forward price projections are based on expectations of growth in PV installed capacity leading to 1760GW by 2030 (IRENA, 2016), up from some 500GW today (IRENA, 2019) and the learning rate (the % cost reduction for each doubling of installed capacity). As Figure 6 shows, historically the PV module learning rate has been 18-22%, but IRENA (2019) suggest 35% between 2010 and 2020. We assume a continued learning rate of 20% for modules out to 2030.

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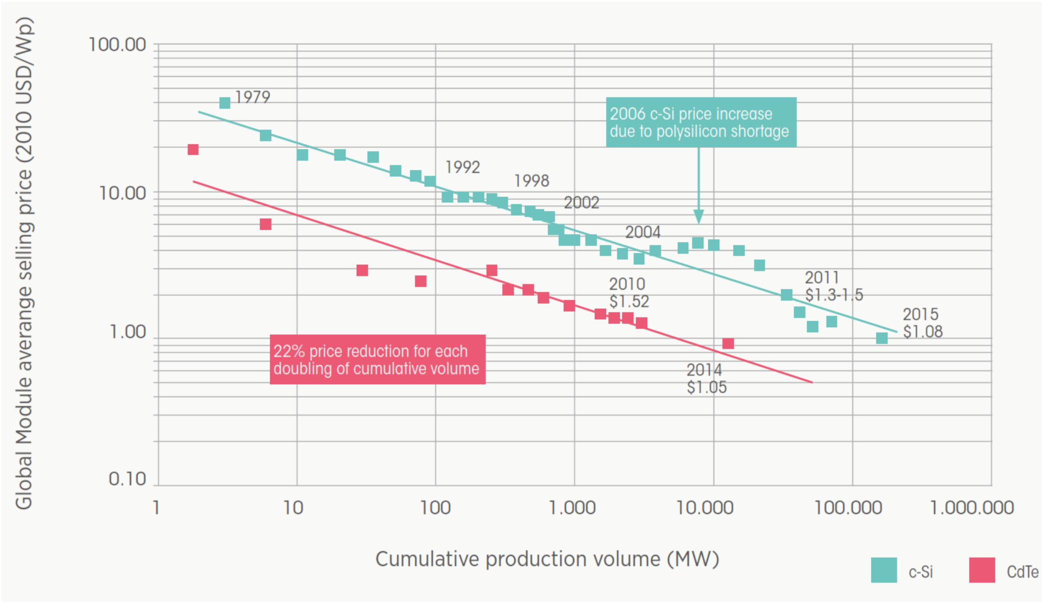

Figure 6 The global PV module price learning curve, 1979 to 2015. Source: IRENA (2012)

Table 1 shows the outcome of this continued learning for PV module prices to 2030.

Table 1 PV module price projections (USD/W_{peak})

Year	Technology					
	Crystalline China	Crystalline Europe (Germany)	Crystalline Japan	Thin film a-Si	Thin film a-Si/u-Si or Global	Thin film CdS/CdTe
2010	2.25	2.71	2.65	2.24	1.89	
2011	1.69	2.15	2.05	1.48	1.55	1.30
2012	0.88	1.24	1.25	0.81	0.84	0.70
2013	0.76	1.03	1.06	0.76	0.65	0.53
2014	0.74	0.86	0.88	0.67	0.58	0.47
2015	0.60	0.64	0.70	0.62	0.52	0.43
2016	0.55	0.58	0.63	0.57	0.48	0.39
2017	*0.50*	*0.53*	*0.58*	*0.52*	*0.43*	*0.36*
2018	*0.46*	*0.49*	*0.54*	*0.48*	*0.40*	*0.33*
2019	*0.44*	*0.47*	*0.50*	*0.45*	*0.38*	*0.31*
2020	*0.42*	*0.44*	*0.48*	*0.43*	*0.36*	*0.30*
2021	*0.40*	*0.42*	*0.46*	*0.41*	*0.35*	*0.29*
2022	*0.38*	*0.41*	*0.44*	*0.40*	*0.33*	*0.27*
2023	*0.37*	*0.39*	*0.43*	*0.38*	*0.32*	*0.27*
2024	*0.36*	*0.38*	*0.41*	*0.37*	*0.31*	*0.26*
2025	*0.35*	*0.37*	*0.40*	*0.36*	*0.30*	*0.25*
2026	*0.34*	*0.36*	*0.39*	*0.35*	*0.29*	*0.24*
2027	*0.33*	*0.35*	*0.38*	*0.34*	*0.29*	*0.24*
2028	*0.33*	*0.35*	*0.37*	*0.34*	*0.28*	*0.23*
2029	*0.32*	*0.34*	*0.37*	*0.33*	*0.28*	*0.23*
2030	*0.31*	*0.33*	*0.36*	*0.32*	*0.27*	*0.22*

Sources: IEA (2017); SolarPowerEurope (2016); IRENA (2016). Note : values from 2017 onwards are modelled using a learning rate of 20% and assumed global growth of PV installed capacity to 17690GW by 2030

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However these are factory gate prices for modules alone and balance of plant must be included (estimated as 15%, principally for wiring costs, following IRENA, 2012) and oncosts for transport and retailing in the study country (estimated as 40%). Table 2 shows the PV price assumptions used in the model.

Table 2 PV prices in model

Year	**Total price**	Module (factory gate)	Other BoS	Sales
	$/Wp	$/Wp	$/Wp	$/Wp
2018	**0.72**	0.46	0.07	0.19
2019	**0.68**	0.44	0.07	0.18
2020	**0.65**	0.42	0.06	0.17
2021	**0.62**	0.40	0.06	0.16
2022	**0.59**	0.38	0.06	0.15
2023	**0.57**	0.37	0.06	0.15
2024	**0.56**	0.36	0.05	0.14
2025	**0.54**	0.35	0.05	0.14
2026	**0.53**	0.34	0.05	0.14
2027	**0.52**	0.33	0.05	0.13
2028	**0.50**	0.33	0.05	0.13
2029	**0.49**	0.32	0.05	0.13
2030	**0.48**	0.31	0.05	0.12

2.4 Batteries

Efforts in battery development, notably for Lithium-ion types, in the past five years have focused largely on the Electric Vehicle market, which requires high energy density, low cost powerpacks. As technology development and innovation has driven prices down, interest in other storage applications has picked up strongly. There is now great activity in utility-scale energy storage research and product development, and also in small scale stationary power applications, including for home energy systems and off-grid power. IRENA (2015) illustrate this interaction between the automotive and power sector markets: "Tesla Motors, an EV producer that uses lithium-ion batteries in its vehicles, is building a production facility in the American state of Nevada to produce 35 GWh of battery cells (equal to global li-ion cell production in 2013), and 50 GWh of battery packs by 2020. The batteries would be used primarily for the company's EV fleet but could also be sold into the power sector and for consumer electronics. While predictions of widespread cost reductions are speculative, the plan illustrates a potential future model for battery innovation." Similarly, the analysts UBS write "The expected rapid decline in battery cost by (more than) 50 per cent by 2020 should not just spur EV sales, but also lead to exponential growth in demand for stationary batteries to store excess power." (Reported in RMI, 2015)

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There are many different cell types, and within any one broad type (notably Li-ion) there are many different chemistries, each of which has different functional characteristics. The model has been designed in a modular form, with battery performance and sizing using generic parameters, but allowing for the specific characteristics of different battery types, such that new battery options can be added to the modelling as they emerge.

For this study, we are interested in the specific end-use of residential-scale off-grid battery storage coupled with generation from solar PV, with relatively rapid discharge on a daily cycle, in what may well be hot and dusty conditions. The set of technical performance characteristics and specifications for batteries is complex, and interwoven: e.g. the number of cycles possible depends directly on the typical depth of discharge. Furthermore, the relationships between these various parameters is highly dependent on the specific battery type and chemistry, and on management systems applied. This modelling seeks to identify key characteristics and realistic ranges of values for each parameter, through which sensitivity analysis of the performance and costs of the system can be performed.

It is not easy to transfer data on battery performance in the literature to this specific eCook application. In particular, battery lifetime is complex, influenced by battery chemistry and construction, by the conditions in the operating environment and by the loads drawn. Leach and Oduro (2015) provide further discussion of these issues.

2.4.1 Battery sizing

For the present work, the required battery capacity is modelled as follows. To the right is a worked example, with illustrative values:

$$E_{discharge} = \left(\frac{E_{batt,avg}}{\eta_{inverter}}\right) \times (1 + \omega_{cable})$$ $E_{discharge}$: Daily battery discharge required (kWh/day) $E_{batt,avg}$: Average electricity input to cooking appliance from battery (kWh/day) $\eta_{inverter}$: Inverter efficiency (%) ω_{cable}: Cable losses (%)	$E_{discharge}$ = 0.60 kWh/day $E_{batt,avg}$: 0.51kWh/day $\eta_{inverter}$: 0.9 (ie 90%) ω_{cable}: 0.05 (ie 5%)
$$C_{batt} = E_{discharge} \times F_{storage} \times \frac{1}{1 - DoD_{min}} \times (1 + F_{decay})$$ C_{batt}: Required battery capacity (kWh) $E_{discharge}$: Daily battery discharge required (kWh/day) $F_{storage}$: Storage oversize factor (days; ie 1 = full charge/discharge each day)	So, C_{batt} = 0.83kWh $E_{discharge}$: 0.6 kWh/day $F_{storage}$: 1

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DoD_{min}: Minimum remaining charge level (%) (typically 20%) F_{decay}: Additional design capacity added to account for the decay loss in capacity of the battery. Default is to add half of the capacity lost by end of life (ie 20%/2 = 10%)	DoD_{min}: 0.2 (ie 20%) F_{decay}: 0.1 (ie 10%)
The evidence base on battery performance and decay for cooking applications (ie high power draw) in high ambient temperature conditions is thin. We adopted Wang et al (2011) which presents a generalised model for graphite-LiFePO4 cells:	
$F_{cycledecay} = A \times exp\left[\frac{-31700 + 370.3 \times C_{rate}}{R \times T}\right] \times I^{0.55}$ So rearranging: $I = \sqrt[0.55]{\frac{F_{cyclesdecay}}{\left(A \times exp\left[\frac{-31700 + 370.3 \times C_{rate}}{R \times T}\right]\right)}}$ I: Ah-throughput, i.e. amount of charge delivered by battery during its lifetime $F_{cycledecay}$: loss of capacity due to charge and discharge over the operating life. Normally chosen to be 20% A: Pre-exponential factor, empirically dependent on C_{rate}, calculated below C_{rate}: discharge current divided by the theoretical current draw under which the battery would deliver its nominal rated capacity in one hour R: Universal gas constant, 8.314 J/mol K T: Battery temperature (degC)	So, I = 3600Ah $F_{cycledecay}$: 0.2 (ie 20%) A: 31630 (see below) C_{rate}: 0.5 (ie full discharge in 2 hours) T: 40degC
Now, $I = Cycles_{life} \times DoD_{avg} \times Full\ cell\ capacity$ So $Cycles_{life} = {}^{I}\!/\!\left(DoD_{avg} \times Full\ cell\ capacity\right)$ $Cycles_{life}$: charge/discharge cycles before battery is replaced I: Ah-throughput, i.e. amount of charge delivered by battery during its lifetime DoD_{avg}: average depth of discharge in cycling	So, $Cycles_{life}$ = 2300 I: 3600Ah DoD_{avg}: 0.8 (ie 80%)

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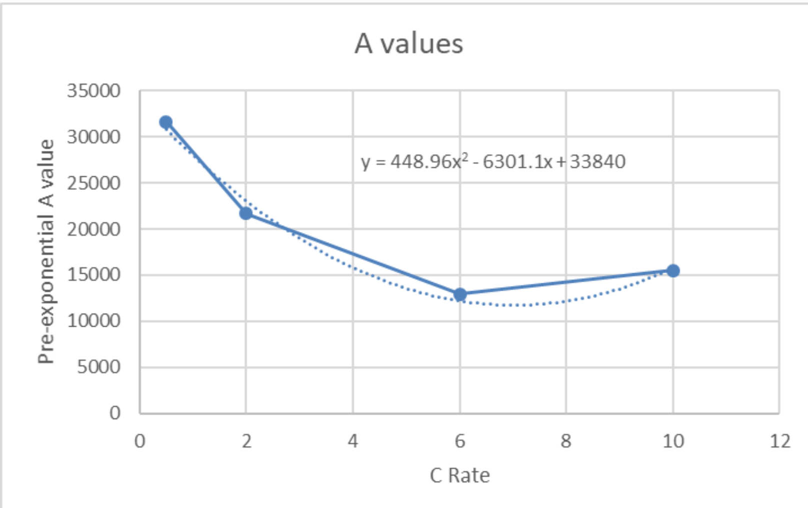
Full cell capacity: 2Ahr, Standard cell size used to derive empirical relationship	2Ah
For the value of A in equation above: Wang et al (2011) present an empirical relationship between A and discrete values of C_{rate} (from 0.5 to 10).  We estimate the continuous relationship as: $$A = 448.96 \times C_{rate}{}^{2} - 6301.1 \times C_{rate} + 33840$$	For C-Rate of 0.5 A= 31630

Thus the cycle life of the battery can be estimated depending on the operating temperature and the current drawn for cooking, and might typically be 2300 cycles, or 6 years of daily use.

2.4.2 Battery prices

Developing clear estimates of current and prospective battery system costs is difficult; IRENA (2015) note that there is a lack of common standards on reported metrics and most companies undertake their own testing, thus reported values in the literature are rarely coming from objective sources. There is much poor practice across the industry and analysis communities, with lack of clarity on whether reported costs are for cells, for packaged batteries or for complete storage systems including thermal protection and controls. There is also typically little said about the types and scales of application for which quoted values

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are relevant. Batteries for Electric Vehicles have received more attention to date than those for stationary power applications, and analysts are clear that future battery developments will largely be driven by the EV market. Thus the projection of future battery prices are undertaken here based on expectations for EVs, with assumptions for the transfer of learning to the eCook market.

More detailed discussion of the historical evolution of battery prices is given in Leach and Oduro (2015). In brief, Figure 7 shows the results of one of the most comprehensive studies, a systematic review of based on 50 data sources. .

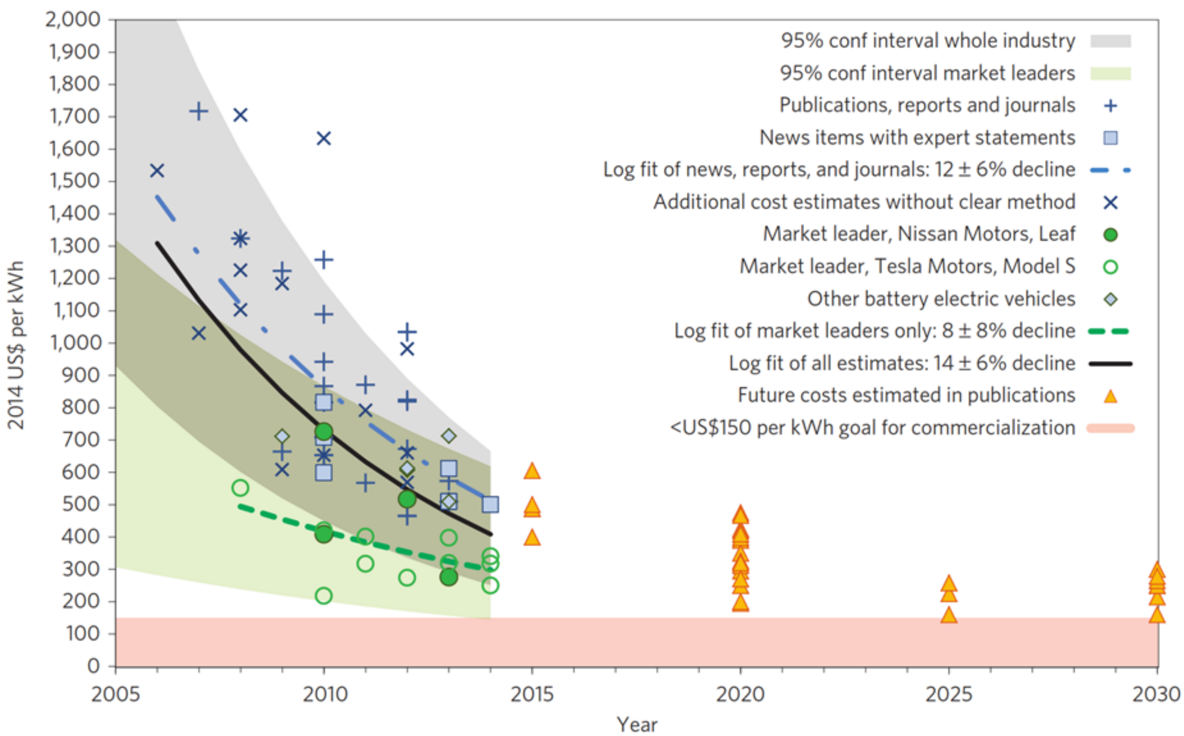

Figure 7 Cost of Li-Ion battery packs for EVs

Source: Nykvist and Nilsson (2015)

The annual Bloomberg New Energy Finance battery price survey has shown that prices more recently have continued to fall, and indeed at a faster rate than anticipated by Nykvist and Nilsson (2015). In the publicly available data, BNEF show only a single set of average historic prices and forecasts, whilst acknowledging that there will be variation around the mean (Goldie-Scot, 2019). Figure 8 shows their most recent results.

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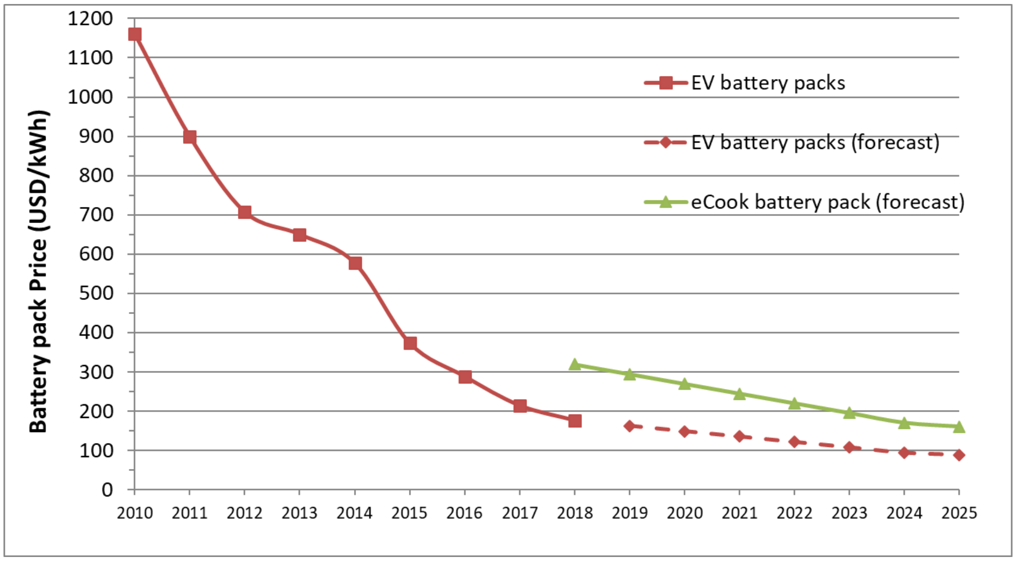

Figure 8 Battery pack price forecasts

Sources: EV battery packs: BNEF 2018 Lithium-Ion Battery Price Survey, in Goldie-Scot (2019); eCook: this study

To transfer these projections for electric vehicle battery pack prices into estimates for eCook battery packs, factors have been used. As suggested by Frith (2017), 51% is added to account for the typical cost premium for stationary battery pack prices. A further 20% is added to reflect the costs for transport and import into Africa, leading to USD270/kWh in 2020 and USD161/kWh by 2025.

The use of static factors of this sort is of course a major simplification. However there is currently little evidence for the real costs of household scale battery pack prices in Africa; this is an area for further analysis. Similarly, there are suggestions that new battery chemistries will enter the market, offering improved performance, longer lifetimes and lower costs, but with limited data and market intelligence available. As such, the uncertainty in battery performance and prices will need to be remain a key focus for modelling sensitivity analysis.

2.5 Balance of System

Besides the PV/grid supply, battery and cooking appliances, a series of additional components is required to ensure an efficient, safe and long-lasting eCook device. In the model these are represented as: battery charge controller, battery management system, inverter and additional wiring.

2.5.1 Battery charge controller

A controller is needed to manage the interaction between the source of electricity (grid or PV panel) and the batteries, to protect the battery from being overcharged or over-discharged, to protect against battery over-heating and to maximise the efficiency of the use of the solar power.

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For PV-based systems, the two main types of charge controller suited for small systems are pulse width modulation (PWM) and maximum power point tracking (MPPT). A PV panel produces its maximum power output (and hence operates at maximum efficiency) typically at around 17v, compared to battery voltage of 12-13.5v. A PWM controller is relatively cheap, but is less effective, as it ties the PV output to the battery voltage, pulling the PV panel to a less efficient operating point. The MPPT controller is able to keep the PV panel at its optimum voltage, effectively converting the excess voltage to current, and maintaining peak power output from the panel.

For larger systems, and those seeking maximum performance, an MPPT controller is a sensible choice. However for the current application, capital cost is a key issue. There is clearly a trade-off to be made between higher capital cost for an MPPT controller, which might allow for a smaller PV panel to deliver the necessary energy for cooking, and the lower cost of a PWM controller, with lower performance.

All PV controllers need to be sized to cope with the systems voltage and the maximum amount of current that might flow through them. To size a PWM controller, the required rated current in amps is calculated from the PV output wattage divided by the PV's peak power output voltage (e.g. 17v) which is taken from the solar PV panel or array specifications. It is recommended to oversize the controller to allow for peak outputs, and to provide a further safety margin against overheating in continuous use. The modelling here allows separate user-defined safety factors for each of these, defaulting to +25% each, following typical industry practice.

The cost of the controller will depend strongly on its rated capacity. However, at any capacity level there is also a wide price range for battery charge controllers, reflecting level of features (e.g. degree of battery temperature protection, efficiency etc.) and overall quality and hence expected life. It would also be expected that significant savings could be made between one-off purchase of a standard charger retail and the cost of a bespoke controller designed into an eCook system.

The current modelling allows the user to choose between PWM and MPPT control, and includes a database of a sample of available standard retail models. An appropriately sized controller is then selected to match the characteristics (notably the voltage and the maximum current expected) of the eCook system. The current database is shown below. In practice the very high cost of MPPT devices suggests that PWM will be used for eCook. The Morningstar SHS-6 to SHS-15 will typically provide the required capacity for the eCook systems modelled to date.

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Table 3 Charge controller database
Source: www.ecodirect.com/

The device is chosen to have a rated load current that exceeds the maximum cooking current expected multiplied by the peak load safety factor and the continuous use safety factor

PWM		
Model	**Rated load current (A)**	**Cost ($)**
Morningstar SHS-6 > 6 Amp 12 Volt	6	24.00
Morningstar SHS-10 > 10 Amp 12 Volt	10	32.00
Morningstar SK-12 > SunKeeper 12 Amp 12 Volt	12	71.00
Morningstar PS-15 (12/24V)	15	96.00
Morningstar PS-30 (12/24V)	30	128.00
Morningstar TS-45 (12/24/48V)	45	167.00
Morningstar TS-60 (12/24/48V)	60	222.00
MPPT		
Model	**Rated load current (A)**	**Cost ($)**
Morningstar TS-MPPT-30 (12/24/48V)	30	382.00
Morningstar TS-MPPT-45 (12/24/48V)	45	478.00
Morningstar TS-MPPT-60 (12/24/48V)	60	598.00

2.5.2 Battery management system

A BMS (Battery Management System) of some sort is essential for any rechargeable battery system. At its simplest, a BMS prevents the battery from operating outside its safe limits, for example through protection against discharge outside current limits. But in practice batteries should be managed more actively than this, with monitoring of state of charge (of the pack or ideally of each cell), measuring temperature and voltage. The quality of control achieved will influence the performance of the battery pack and also its degradation and ultimate lifetime.

The functions above can all be performed by a dedicated 'battery management system'. However, high power batteries on the market now are most commonly sold in packs comprising sets of cells chosen to match each other well and assembled in parallel or series to deliver the required voltage and current discharge capability. These packs all contain in-built protection circuits of one sort or another. As such the BMS functions can be split between the battery pack itself and the charge controller, obviating the need for a standalone BMS. The current study thus does not model the need for an additional BMS, instead specifying charge controllers that perform the necessary functions. For a bespoke eCook design, batteries, BMS and charge controller could be integrated in different configurations, and further research will be

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needed to determine the optimal design, balancing performance, lifetime and cost within necessary safety limits.

2.5.3 Inverter

It is possible to cook by connecting a DC hotplate directly to a battery pack. However, to achieve the required power for cooking from the hotplate (eg 500W to 1000W) this would imply very high current flow in the cables to the hotplate with commensurate losses. It is also difficult at present to buy high power DC hotplates. It is certainly feasible that a bespoke DC hotplate could be developed to integrate with the envisaged PV-battery cooking system.

However an alternative approach is the use of a DC to AC inverter, allowing the use of readily available and low cost AC electric hotplates, as well as other AC cooking appliances (eg a pressure cooker). The other advantage of integrating an inverter is that the household could potentially use the resulting AC power for other purposes, using conventional appliances: lighting, charging mobile phones, radio/TV etc.

An inverter takes the constant voltage of a DC supply and chops it up using power electronics, recombining it to replicate the time-varying voltage of an AC supply. As for charge controllers, there are different inverter technologies available, offering varying quality in the output power. There are three main types (https://www.solar-electric.com/learning-center/inverter-basics-selection.html/): sine wave, modified sine wave and square wave. Sine wave inverters produce the closest replica to a true AC and can power all types of equipment. The square wave produces a crude replica, with the voltage switching from positive to negative at the required frequency, but with sharp changes of polarity. They will run simple devices, but normally with reduced efficiency and electronics often will not operate. The modified sine wave inverter introduces one or more additional voltage steps as the polarity switches, providing a closer approximation to the pure sine wave. Most devices will operate acceptably well with a modified sine wave. However, this depends on the quality of the power electronics built into the device, and is difficult to predict.

There is a wide range of specifications and prices for inverters on the market. The current model includes a small database of popular types. The sizing is based on both the continuous power rating required, to meet the anticipated cooking loads and the 'surge' rating, which is the maximum power the inverter can supply for a short period, to cope with the high start-up load that some devices draw. In practice modern inverters can typically cope with a surge of up to 300% for 3 to 15 seconds, which is sufficient to cope with the load profile of almost all appliances. Inverters are not 100% efficient: the model includes a user-defined value for efficiency, defaulting to 90%. The efficiency affects the required battery sizing and hence the PV sizing (or power drawn from the grid).

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Table 4 Inverter database
Source: www.ecodirect.com/

Pure sine wave (12V)		
Model	**Inverter output continuous load (kW)**	**Cost ($)**
Samlex PST-1000-12A	1.0	379.26
Samlex PST-1500-12A	1.5	478.00
Samlex PST-2000-12A	2.0	626.22
Modified sine wave (12V)		
Model	**Inverter output continuous load (kW)**	**Cost ($)**
Samlex SAM-1000-12	1.0	96.29
Samlex SAM-1500-12	1.5	174.93
Samlex SAM-2000-12	2.0	251.75
Samlex SAM-3000-12	3.0	367.50

2.5.4 Additional balance of system

The rest of the model looks at the major components as individual items, sizing and choosing them from databases of typical options on the market, rather than attempting an engineering design of an integrated whole system. In terms of impact on likely costs of a real system, this brings both positive and negative effects. A bespoke eCook design should be able to achieve some cost savings through integrating functionality, eg in battery control, and more precise sizing of components. However there will also be additional costs not captured by assuming a collection of standalone components, eg system wiring.

To avoid overly-optimistic assumptions, the potential benefits of tighter system integration in mass-market eCook design are ignored at this stage. However the additional balance of system, such as wiring, is reflected in a user-defined parameter, defaulting to an additional 5% added to the total system investment cost.

2.6 Cooking appliances

The model described here was developed as part of the Innovate-UK funded study and intended to be applied using cooking data collected in diary studies in Myanmar, Zambia and Tanzania. Working papers are available at https://www.mecs.org.uk/working-papers/. In the second phase of each cooking diary study period, participants transitioned to cooking with electricity. The two most common categories of cooking device used were simple hotplates, used with conventional cooking pots, and Electric Pressure Cookers (EPCs), mainly used for cooking the 'heavy' foods, such as beans and meat stews, that require longer cooking.

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The data from those studies was used to represent the energy required for cooking using different fuels and using electricity, and as such the current version of the model was set up to represent hotplates and EPCs. The key additional data required is on cost: devices were assumed to be either low cost two-ring hotplates purchased for USD20, or EPCs purchased for USD50. Leary et al (2018) provide a thorough review of EPCs.

2.7 Component lifetimes and replacements

Each component is assigned a technical lifetime, within an overall system modelling horizon of 20 years, chosen as it reflects the notional lifetime of the longest lived major component, the PV. The battery lifetime is derived from the decay model above. Component replacement is modelled throughout the system life, with additional capital cost added each time a replacement component is needed. The model allows for changes in the cost of components over time, such that replacements are made with the costs expected at the time of replacement. This is most significant for the batteries, for which significant cost reductions are projected, and which will certainly require one or more replacements during the 20 year system lifetime. Table 5 shows the assumptions made for lifetime and replacement cost parameters. All parameter values are user-definable and so are open to sensitivity analysis.

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Table 5 Component lifetime assumptions

Component	Lifetime (years)	Price trajectory	Notes
Overall eCook system	20		
PV	20	Decline; learning model	So replacement not considered
Battery	Calculated	Decline; learning model	Based on operating temperature and C-rate
Inverter	10	Decline; 2% per year	
Charge controller	6	Decline; 2% per year	
Cooking appliances	5	Constant	

2.8 Business models and investment financing

The model is structured to calculate the costs required to deliver the electric cooking service for twenty years, including replacement costs for the other components during that period.

The basis of the service fee calculation is a levelised costing of the cooking service, expressed as cost of cooking per month. Black (1984) provides a useful overview of the approach plus illustrations of different applications. The most common form of levelised costing is that for energy supply, where it is the basis for example of figures quoted for cost per unit of electricity from a solar PV installation. However Black (1984) notes that its more general use is simply: ”to determine the revenue required to recover the cost of a service”. This can be supply of energy, of water, or as in this case, the supply of the cooking service.

System cost is the sum of operating costs (grid electricity purchase, traditional fuel purchase), initial capital and installation costs and component replacement costs. Costs are discounted back to present day values using a user-defined discount rate. The cost basis throughout the model is to use real costs, ignoring the action of inflation, and hence a matching real discount rate is applied. The key output metric is the net present cost of cooking per month, which can be directly compared to the cost of traditional fuel purchases to undertake the same cooking.

The core business model is to envisage a supplier of the electric cooking service, who pays the initial and replacement capital costs over the twenty year period, in exchange for a daily or monthly user fee. It is of course unrealistic to imagine that a low-income user would make any form of agreement for twenty years. A twenty year financing model could reflect some form of utility-based business model, where the electricity supplier bears the risk and recovers the investment costs through an additional fee, alongside the regular bill. Some other risk-bearing arrangement with the same effect is conceivable, if installation

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of eCook devices is made as part of national energy access infrastructure, or via development aid or carbon finance.

The more traditional model would be for cost recovery over a shorter period, as for solar home systems. The model thus incorporates a shorter time period for this form of commercial business model. The time period is user-definable (defaulting to 5 years). The normal practice in similar markets is that after the end of the financing period the ownership of the equipment transfers to the user. This means that responsibility for further component replacements also transfers to the user, with the risk that the system falls into disrepair and thus dis-use when a major component fails. Further innovation in business models may be needed to cater for this high capital cost type of appliance and service.

2.9 Fuel/appliance stacking

The model seeks to represent the energy used to meet a household's daily cooking requirements. This can be met by an eCook system sized to meet the full cooking load itself, or by a combination of a smaller eCook system and fuel stacking with a traditional fuel (eg charcoal, LPG, kerosene, firewood) and/or grid electricity directly. The proportions of each source are user defined.

The characteristics of each energy source are defined by parameters for:

- Traditional fuels: calorific value, CO_2-eq emissions per kWh, price per kWh
- Grid electricity: marginal CO_2-eq emissions per kWh, price per kWh for a series of tariff bands (free lifeline plus up to 3 tariff bands can be user-defined)

The parameter values are all user-definable, and will ideally come from the specific area being studied. Fuel and electricity prices in particular vary strongly by location and change over time, and electricity emission factors vary by country. The default calorific values and GHG emission factors for traditional fuels are shown below. These can be tailored if needed.

Table 6 Fuel characteristics

Note: the GHG emission factor for firewood depends on assumptions about the sustainability of wood harvesting. It is assumed here that wood is harvested sustainably, with replanting and regrowth, and hence the low emission factor reflecting non-CO_2 emissions

Fuel	Calorific value (kWh/kg, lower heating value)	GHG emissions factor (kg CO2-eq emissions per kWh)
Charcoal	7.9	0.32168
Firewood	4.1	0.015
LPG	12.6	0.2303
Kerosene	11.9	0.2574

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2.10 Treatment of uncertainty

There are a wide range of uncertainties in the design, sizing and costing of a system to deliver cooking services. The modelling distinguishes between parameters for which the values are uncertain due to:

- different or varying household cooking needs and practices
- uncertainty in appropriate values for parameters
- different financing assumptions
- changes in parameter values over time

2.10.1 Different or varying household cooking needs and practices

The cooking diary studies gathered data on the fuel use for each 'heating event' (meal, water heating etc) each day by each household, in the three countries studied for the Innovate UK project, and then in Kenya. Detailed statistical analysis has been undertaken, and this is reported in the Working Papers on the individual country cooking diary studies, available at www.mecs.org.uk/working-papers/

Variation in the energy required between households per day will clearly depend on the number of people for whom each meal is being cooked and the foods being cooked (and other cooking event types, such as water heating). However even after accounting for such differences, considerable variation remains evident in the cooking energy used by different households. Observations of cooking, and discussions with participants, shows that cooks vary in their practices, for example the use of lids on pots and the degree of care in controlling heat output from fuels or electric hotplates.

Whatever the source, any variation in energy use per household has implications for the design of an eCook system: a traditionally-fuelled stove has a potentially unlimited fuel supply, but a battery-eCook device has a fixed energy capacity. Running out of energy mid-meal or mid-day will frustrate the cook. Fuel stacking is routine for many households, and it would be difficult (or expensive) to size an eCooker such that it could cope with the most extravagant meals cooked for an extended family. An acceptable trade-off will be needed between ability to meet varying cooking demands and system cost, which may well imply that different system sizes are needed to suit different household circumstances and priorities.

Variation in cooking energy that relates to cooking practices is open to behaviour change or the introduction of more efficient cooking equipment. As such, the trade-off of eCooker capability against cost is further influenced by the potential for higher energy users ('less efficient' cooks) to change their practices so that a smaller eCooker could meet their needs.

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Table 7 shows a summary of the variation in cooking energy used in the Tanzanian cooking diary study, for traditional fuel use in phase 1 and then electricity use in phase 2. To exclude outliers the table shows the average energy use and then the first and third quartiles from the distribution of cooking energy use. So for electricity use in phase 2, the median energy use in a day across all households and all days in the study was 7.4 MJ, but 25% of household-days required 3.9 MJ or less and 25% required 11.4MJ or more.

Table 7 Total daily energy consumption (MJ/household/day) in Tanzania – use of single fuel in a day
Source: https://www.mecs.org.uk/wp-content/uploads/2019/10/eCook-Tanzania-Cooking-Diaries-Working-Paper-13-10-19-JL-COMPRESSED.pdf

	Daily energy consumption (MJ/household/day)					Proportion of days with heating event					Household members (mean of means)
	n	Mean	Q1	Median	Q3	Breakfast	Lunch	Dinner	Water heating	Food for baby	
Charcoal (Phase 1)	31	84.3	50.4	80.4	115.6	83.9%	87.1%	96.8%	96.8%	12.9%	6.1
Kerosene (Phase 1)*	7	6.0	3.5	3.9	9.8	85.7%	42.9%	28.6%	71.4%	0%	3.2
LPG (Phase 1)	109	17.2	5.6	14.8	22.2	87.2%	67.0%	79.8%	81.7%	26.6%	4.1
Electricity (Phase 2)	423	8.8	3.9	7.4	11.3	90.5%	78.3%	81.6%	83.9%	36.6%	4.2

* based on records from one household only

For different applications, the model can be tailored and applied to explore the above uncertainties in cooking loads in several different ways:

- Design for 'average' (mean or median) energy use per day, and explore the sensitivity of the resulting eCook system sizing to variation in cooking energy demand
- As a variation on the above, compare specifically the eCook sizes needed to deliver on the median and the 25% and 75% quartile points
- Explore the implications for required system size if cooking loads are reduced, for example through adoption of 'more efficient' cooking practices or the use of more efficient electric appliances

2.10.2 Uncertainty in appropriate values for parameters

All parameters used to characterise the eCook system are subject to some degree of uncertainty in their values, dependent for example on the level of detail in the model (eg limited range of choices of inverter,

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and fuel prices estimated at the city-wide scale) and the reliability of the data source (eg the inverter price data are taken from an online catalogue, and the fuel prices might be taken from international datasets).

The model has been developed and applied with a series of principles in mind:

- transparency about assumptions and data used
- flexibility in model design to allow updates in data and in model structure
- explicit acknowledgement of uncertainty, avoiding single point results but instead showing ranges, dependent on the input data

In the first application of the model in 2015, the latter point was followed by showing the effect of different parameter values in the cost of cooking in three ways, as shown in Figure 9. A range of costs is portrayed by each bar, showing the difference between 'optimistic' assumptions (better technical efficiencies and lower component costs, and for traditional fuels, lower rates of price increase) and a more 'pessimistic' scenario; sensitivity to the discount rate assumption is shown by the pairs of bars for eCook; the influence of cooking load, represented by 'low cook' and 'high cook' demands.

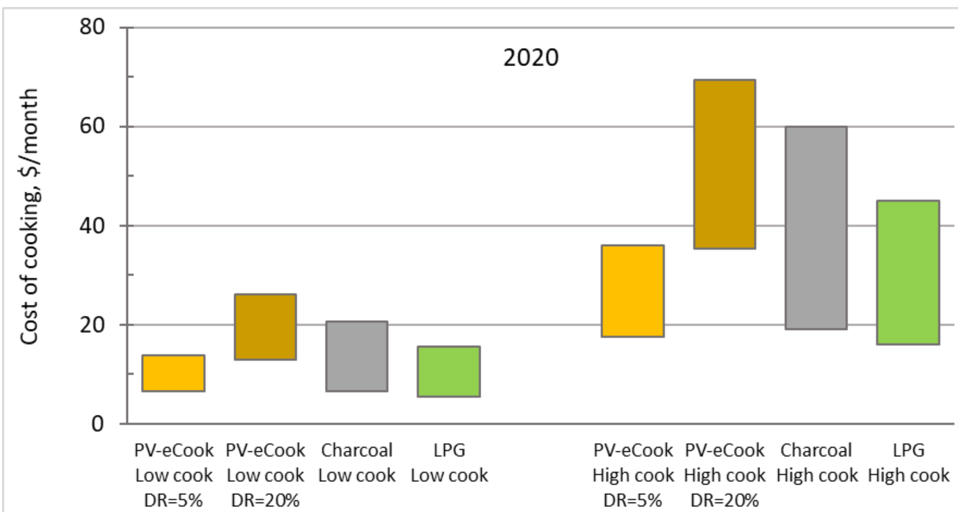

Figure 9 Treatment of uncertainty in Leach and Oduro (2015)
Note: this was a representation of a typical east African application, based on secondary data

Interpretation of the bars can be difficult, as the range in each case includes the effect of several factors, and bars of alternative cooking options will frequently overlap. In the above example, the main factor underpinning the lengths of the charcoal and LPG bars is the assumption about the price of the fuels, which was between USD0.23/kg and USD0.57/kg for charcoal and USD1.3/kg and USD3/kg or LPG. The bars for eCook reflect a variety of technology performance and cost assumptions, but driven mainly by

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assumptions about battery costs, of between USD200/kWh and £300$/kWh. Knowing the underpinning parameter value assumptions, conclusions can be drawn, such that for the system in Figure 9: with lower cost assumptions about eCook, the overall cost of cooking will be less than that for charcoal or LPG in all but areas with very low traditional fuel prices.

More recent application of the model follows a similar approach, with the sensitivity to uncertainty or alternative scenarios for different parameters, as suits the research questions being asked; see section 3.

2.10.3 Different financing assumptions

The model calculates the levelised costs of the cooking service, expressed as cost of cooking per month, assumed to be delivered as a service by some form of investor who pays for the initial capital and replacement capital costs during some financing period.

Variations in the business model can be explored in at least two ways:

- By exploring the influence of different discount rates, eg from 5% (equivalent to an almost risk-free rate, consistent with investment made, or subsidised, by national government) to 20% (representing a commercial investor seeking rapid return on investment).
- By exploring the influence on cost of cooking when the capital costs are assumed to be paid off over alternative time periods

2.10.4 Changes in parameter values over time

The model asks the user for the year in which the eCook system is to be installed. All of the key parameter values are specified by year, either through lookup to databases of values by year (eg for PV and battery prices) or through a user-specified annual growth rate from a baseline year (eg for traditional fuel prices).

The results for cost of cooking are reported for the chosen installation year. The model uses real costs throughout (ie ignoring inflation) and 2018 is used as the cost baseline.

Installation in a particular year (eg 2020) will therefore use capital cost estimates for initial investment in 2020, plus replacement costs thereafter, including any change in real prices assumed to occur (eg battery replacement in 2026, using the battery prices relevant for 2026). The reported cooking costs will be in 2018 US Dollars.

2.11 Model implementation

The model is implemented in Microsoft Excel, using a set of Visual Basic macros to automate certain processes. The structure is modular, with separate tabs for each major component and modelling process.

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The existing implementation is intended to be user-friendly but remains a research tool, lacking a comprehensive graphical user interface. Drop-down boxes are used for discrete choices and parameter values can be entered directly throughout the spreadsheet, with cells intended for user-input indicated by red outlines. The screenshot shows the front tab, where key user choices are brought together, along with reporting of key results.

This is a simulation model and not particularly computationally intensive. The input data and output results can be saved at any moment to a tab which accumulates results, such that a series of scenario or sensitivity runs, eg incrementing the cost of charcoal, can be run very easily.

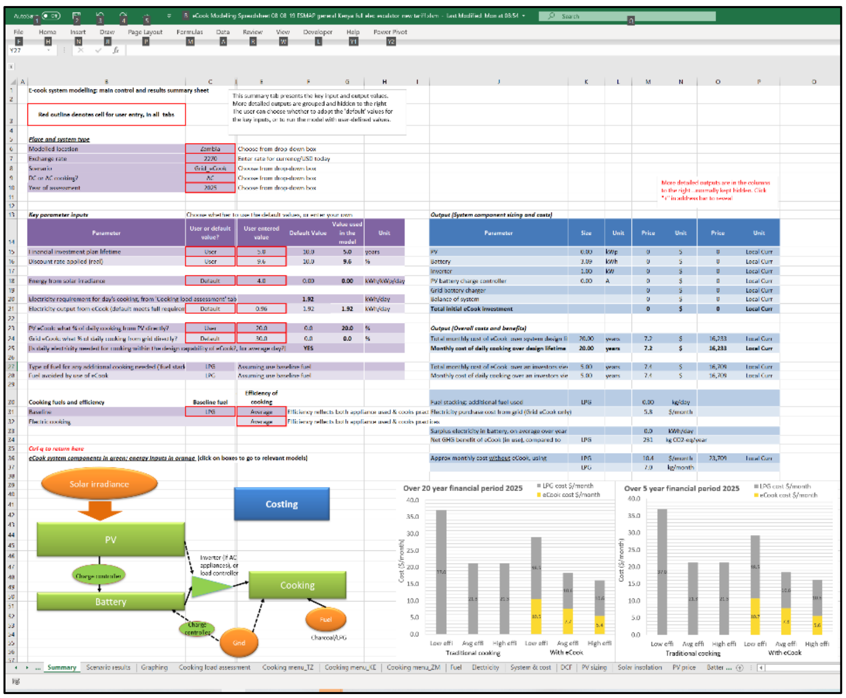

Figure 10 Screenshot of eCook model front page

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3 Applications

3.1 DfiD PEAKS, 2015

The model was initially developed as part of a study commissioned by DfiD through the CEIL-PEAKS Evidence on Demand service. The application of the model was made using data from secondary sources and intended as a first scoping and proof of concept of the eCook concept. The report is available as Leach and Oduro (2015) at a link from "Research Question 1" here: https://elstove.com/dfid-uk-aid-reports/.

The results includes those shown in Figure 9, and led to the conclusion that "*the core concept of a PV-battery-electric cooker as a substitute for purchased cooking fuels is a realistic one. The range for monthly cost for the system in 2020 is expected to be very similar to that for charcoal and LPG cooking, implying that a system actually realised with various levels of technical and cost performance could compete effectively with traditional fuels, in various contexts*".

3.2 Innovate UK

In 2018 the model was redeveloped and extended within an Innovate UK, Gamos and UK Aid funded project designed to assess the opportunities and challenges that lay ahead for eCook in high impact potential markets. A Global Market Assessment (Batchelor et al, 2018) was undertaken and from that three initial target countries were selected for detailed study: Tanzania, Zambia, Myanmar. Cooking Diary studies undertaken in each country form the current basis of the cooking demands used in the model, and various data currently in use were collected in other parts of the project eg traditional fuel prices).

Working papers on each part of the project, for the three countries studied are available at https://www.mecs.org.uk/working-papers/. Similar work was undertaken in Kenya by the Low Cost Energy-Efficient Products for the Bottom of the Pyramid (LCT) project funded by DfID/UK Aid, EPSRC, RCUK & DECC (now BEIS) through the USES programme; equivalent working papers are available at the same link.

The model was not applied systematically to the results of each of the studied countries during the Innovate project. Instead, a deeper analysis of the data collected during that project and application of the model was subsequently carried out during 2019 within the MECS programme. This analysis forms a core component of the report on electric cooking developed between MECS and ESMAP discussed in section 3.3. However the model was used during the Innovate project period to support activities during the Myanmar and Tanzania country studies, as discussed below.

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3.2.1 Modelling eCook in Myanmar – inputs to a participatory cooking workshop

The national stakeholders' workshop 'Innovative Research on Electric Cooking and Beyond' took place at the Department for Research and Innovation, Yangon, Myanmar from the 29th to the 31st January 2018, to explore the opportunity for eCook in Myanmar. The workshop targeted government stakeholders, with representatives from key ministries attending. The workshop was conducted for three days; on the first day participants were acquainted with the eCook concept and relevant national programmes. On the second day, participants carried out practical experiments with eCook appliances and worked in small groups to design an eCook product/service tailored to the needs of everyday cooks in Myanmar, using the eCook model to test out the design and cost implications of their ideas. On the final day, participants summarised the key opportunities and challenges that await for eCook in Myanmar.

As part of the eCook product/service design small group work on day 2, a modelling exercise was carried out to calculate the relative cost of each group's solution compared to the cost of other popular cooking fuels. Repayment horizons of 3, 5 and 20-years were modelled to represent different private sector and utility business models, with 'pay-as-you-go' business models. Two optimised systems were modelled based upon the data obtained during the workshop with comparable tests carried out in the REAM office. Figure 11 shows the payment schedules for the first of these, which was designed to meet a household's everyday needs, but with an optimised all electric system with monthly costs ranging from 6,000-10,000 MMK (4-6.5 USD) for Grid-eCook and 8,500-19,000 MMK (5.5-12.5 USD) for PV-eCook. The second optimised system was designed to cook just rice two times a day and has monthly costs ranging from 1,500-2,500 MMK (1-1.5 USD) for Grid-eCook and 2,500-6,000 MMK (1.5-4 USD) for PV-eCook.

A full report of the workshop and results of the modelling is available in a MECS Working Paper at https://www.mecs.org.uk/wp-content/uploads/2019/10/Modelling-eCook-in-Myanmar-%E2%80%93-a-discussion-of-the-outcomes-of-a-participatory-cooking-workshop-12-3-18.pdf

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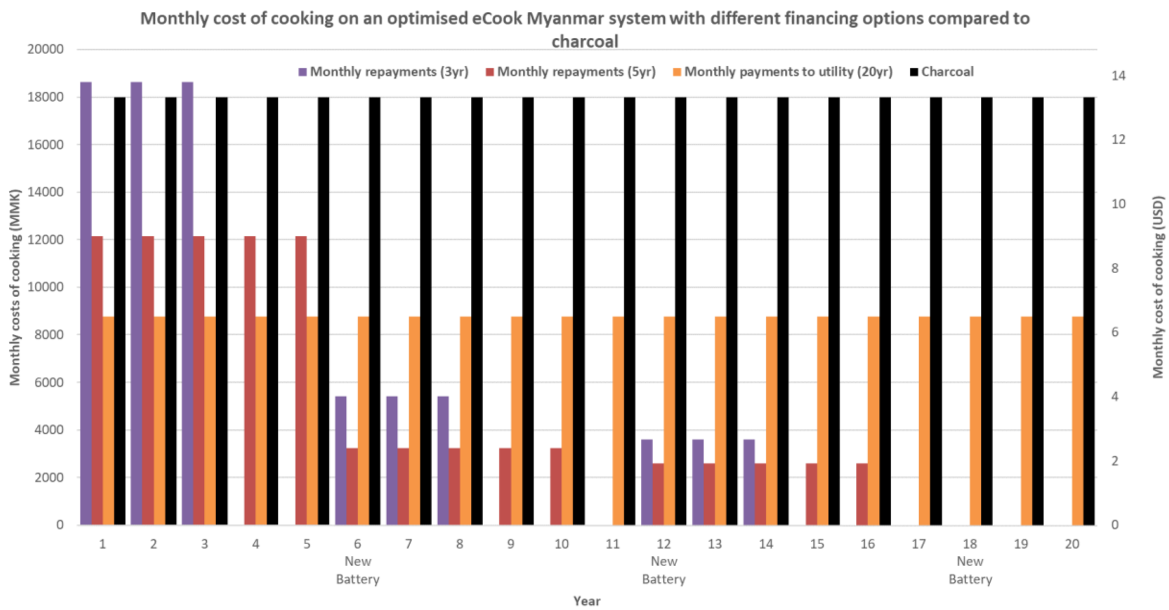

Figure 11 Payment schedules of an optimised PV-Cook system designed to meet the cooking needs of a household of six people.

3.2.2 Modelling eCook in Tanzania: input to the national stakeholders solar electric cooking workshop

The National Stakeholders' Solar Electric Cooking workshop was held at TaTEDO offices in Dar es Salaam on 24th and 25th April 2018, to explore the opportunity for eCook in Tanzania. The workshop was conducted over two days; on the first day participants were acquainted with the eCook concept and lessons coming from the other parts of the Innovate study in Tanzania, while on the second day attendees undertook a 'Design Challenge' in teams, experimenting with eCook appliances, measuring cooking energy use and then using the eCook model to characterise and cost a system of each team's choosing.

Each team were judged on five criteria; i) Target market and impact ii) Business model, iii) Responding to cooks' feedback, iv) Technical viability and v) Innovation. The winner group was "Nishati ya gharama nafuu" group (Figure 12). The features of their design were:

- The Cost and ownership
    - Low cost between Tshs 30,000-35,000
    - Pay as you go system implemented by a private company/agency and categorized according to the income level of the customer.
    - Initial payment of 20% which is about Tshs. 6,000-7,000 per month.

- Marketing strategy
  - social media campaigns
  - Local campaign.
- Cooks feedback
  - Energy serving
  - Time management
  - Tidy
  - No smoke and ashes
- Technical viability
  - Backup charging of batteries through grid.
  - Maintenance and replacement of parts to be taken care by private company/agency.
- Innovation
  - A system should have ports for charging other appliances like torch light, TV, radio and phones and cooking heating water capacity be around 1.5kW.

Figure 12 The winners of the eCook Design challenge; "Nishati ya gharama nafuu" group with their prizes

A full report of the workshop is available in a MECS Working Paper at https://www.mecs.org.uk/wp-content/uploads/2019/09/THE-NATIONAL-STAKEHOLDERS-WORKSHOP-REPORT-15-3-19.pdf

3.3 MECS-ESMAP report

The Innovate project produced substantial new empirical evidence on how people cook, the energy they use to do it, and their preferences concerning alternative cooking appliances and fuels, for Tanzania, Zambia and Myanmar; similar data has been collected in Kenya through the linked LCT project. The eCook model was being developed in parallel to this work, and was used during the life of the project as described in section 3.2. However with completion of the analysis of the datasets, further eCook design modelling has been possible. This has been undertaken during the second half of 2019 under the auspices of the MECS programme, and linked to development of a report on electric cooking, undertaken between MECS and ESMAP. The report will be published shortly. The sections below show some of the modelling that has been undertaken.

3.3.1 Overview of methodology and cases

The daily energy demand figures from the cooking diaries were used as inputs to the eCook model to explore the potential viability of a range of eCooking solutions in a set of different contexts. The contexts considered relate to different combinations of the characteristics of the electricity grid and the cost of traditional fuels, for case study regions.

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Table 8 shows a matrix of these two factors, and what is proposed to be appropriate eCook applications in each combination. If baseline fuel prices are high compared to grid tariffs or the cost of standalone solar systems, 100% electric cooking is likely to be economically viable. However, as the relative cost of baseline fuels decreases, then electric cooking must become more efficient to remain cost effective, e.g. by cooking 50% of the menu on EPCs. Finally, when baseline fuel costs are relatively low, electric cooking must offer substantial efficiency gains over baseline cooking practices to compete, e.g. by using EPCs solely for boiling ‘heavy foods’. Where the existing grid is strong, AC electric cooking, without use of a battery, may be viable. However in weak or otherwise constrained grid situations (whether national- or mini-grids), battery support would enable electric cooking.

Table 8 Relationship between baseline fuel costs and modelled scenarios in strong, weak and off-grid contexts
In strong and weak grid contexts, baseline fuel cost is relative to the grid tariff, whilst in off-grid contexts, it is relative to the costs of standalone solar systems

	Strong grid	**Weak grid**	**Off-grid**
High baseline fuel costs	Range of appliances for 100% of menu	Battery-supported range of appliances for 100% of menu	Solar powered battery-supported range of appliances for 100% of menu
Medium baseline fuel costs	EPCs for 50% of menu	Battery-supported EPCs for 50% of menu	Solar powered battery-supported EPCs for 50% of menu
Low baseline fuel costs	EPCs for boiling ‘heavy foods’ only	Battery-supported EPCs for boiling ‘heavy foods’ only	Solar powered battery-supported EPCs for boiling ‘heavy foods’ only

Three fuel/appliance stacking scenarios were therefore modelled in each context:

1. 100% electric cooking, stacking inefficient and efficient electric cooking appliances;
2. 50% electric cooking with efficient appliances, stacking with baseline fuels for the remaining 50%;
3. EPCs for boiling heavy foods only (Tanzania case only).

The choice of 50% or 100% of daily cooking being done with electricity reflects the opportunity for larger or smaller eCook devices. The third case represents an even smaller eCook concept, used just for the dedicated purpose of pre-cooking beans.

The modelling explores off-the-shelf Alternating Current (AC) electric cooking appliances for strong grids and battery-supported Direct Current (DC) or hybrid appliances that can run on both direct AC and battery-supported DC for weak grids and off-grid solutions. In remote off-grid regions, it focusses on solar powered battery-supported eCooking. The analysis looks at the costs for eCooking expected in the near term, 2020, and with projections to 2025. The 2025 analysis accounts for important trends: (a) reducing costs for an eCook system through technical and organisational learning; and (b) the assumption of

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increasing charcoal, LPG, firewood and kerosene prices. Both utility and lease-to-own business models are modelled with 20- and 5-year repayment horizons respectively, and costs are compared to those for a household cooking with traditional fuels.

Table 9 summarises the range of contexts and appliance options that were modelled across the four countries, assembled into a set of five cases.

Table 9 Local contexts and battery- eCook systems analysed

Context		**Power supply**	**% cooking; Appliances**	**Stacking with**
Urban	Nairobi, Kenya	Grid	100%; EPC, rice cooker, hotplate	Charcoal, Kerosene, LPG
			50%; EPC	
	Lusaka, Zambia	Grid	100%; EPC, hotplate	Charcoal, LPG
			50%; EPC	
Rural	Naung Pain Lay, Myanmar	Mini-grid	100%; EPC, rice cooker, induction hob, electric frying pan	Firewood, LPG
			50%; EPC	
	Kibindu, Tanzania	Mini-grid, off-grid (solar)	EPC (boiling heavy foods only)	Charcoal, LPG
	Echariria, Kenya	Off-grid (solar)	100%; EPC, hotplate	Charcoal, Kerosene, LPG
			50%; EPC	

Figure 13 provides an illustration of the sort of systems considered.

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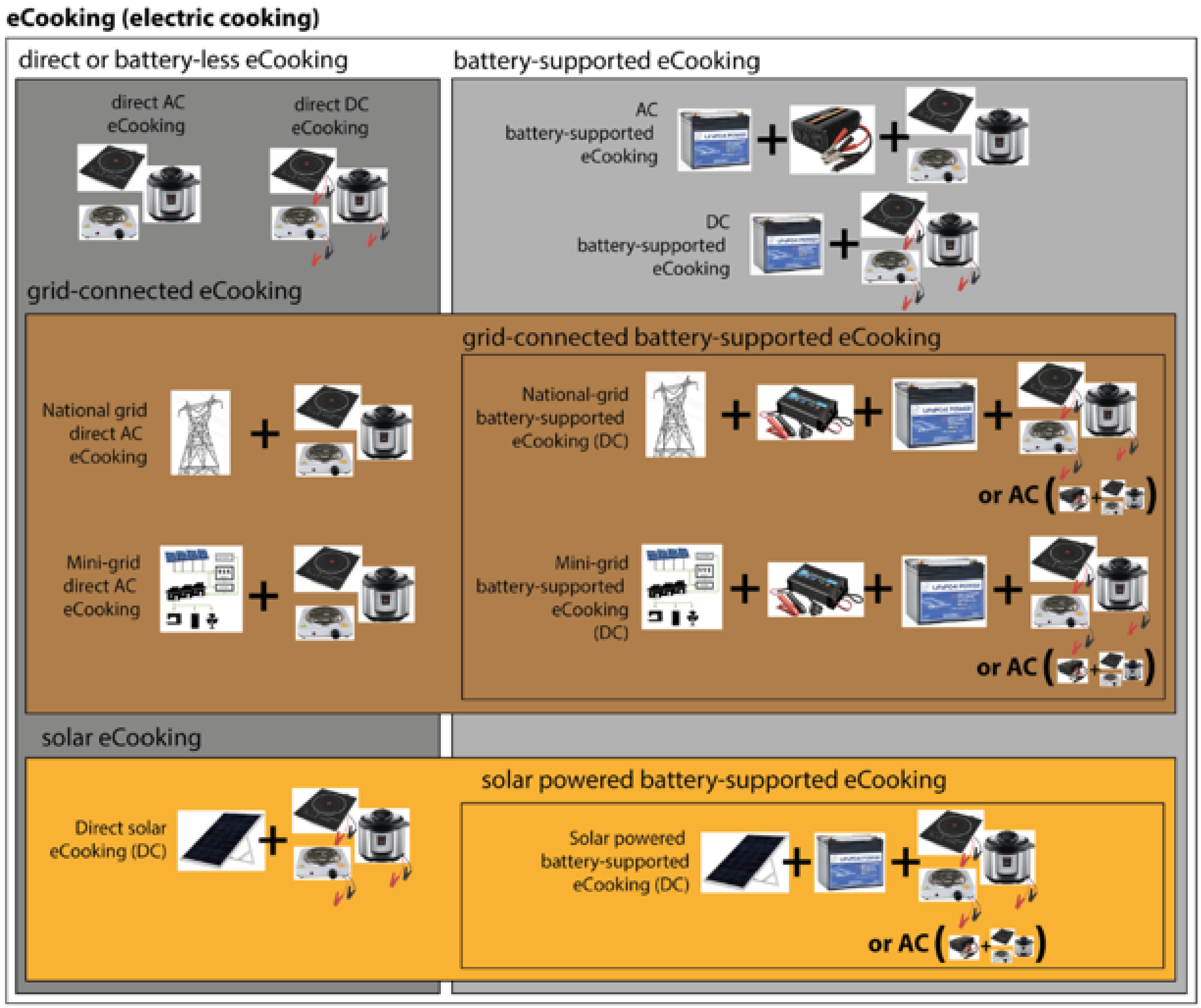

Figure 13: Typology of electric cooking devices for strong, weak and off-grid regions

3.3.2 Cooking loads

Table 10 shows the median daily energy consumption figures from the 100% electric cooking stage of the cooking diaries in each country, whilst In the 100% battery-supported eCooking scenarios, the techno-economic model sizes the battery to meet the median daily cooking load found from the cooking diaries analysis for that country. In hybrid AC/DC systems, it is sized to 1/3 of this value. It is assumed that in the latter, 50% of the cooking load is battery-supported and 50% direct AC, but that cooks would be willing to cook with energy-efficient appliances, using the battery, during blackouts. On the majority of days, the modelled eCooking devices in the 100% electric scenarios would therefore have sufficient capacity to meet all of that day's cooking demand. On the days when cooking demand is higher, for example on special occasions where many guests are received, fuel stacking is assumed to occur. The costs of

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traditional fuels to cover this fuel stacking have been assumed to be negligible in the 100% electric scenarios, as participants in the cooking diaries studies recorded negligible traditional fuel use during the 100% electric cooking phase. However, they are fully costed in the 50% electric cooking scenarios.

Table 11 shows comparable figures for the baseline fuel period in each country. Inspection of the distribution of daily cooking demands across the cooking diary samples shows that it is not a normal distribution, with a substantial tail towards higher loads – representing a mixture of days on which special meals are cooked, and some cooks who are unusually energy inefficient in their practices. Thus the median is lower than the mean, and by choosing the median in this analysis, we are representing the sort of eCook device that would be needed to cook the food on the majority of days.

Detailed analysis of the Kenya cooking diaries data, at the dish level, allows us to deduce that EPCs use roughly half the energy of electric hotplates across the full range of dishes that they are able to cook. Further analysis of the Kenya cooking diaries dataset suggests that with minimal training, households would choose to use an EPC to cook half their menu if it were the only electric appliance available.

For this study, the electricity demand of a typical household stacking an EPC with their baseline fuel is estimated by simply multiplying the measured median daily energy consumption figures for 100% electric cooking presented in Table 10 by one third. This proportion is derived from the observations described above of 50% of the menu cooked on EPCs, using 50% of the energy of the hotplate. The accompanying energy for baseline fuels is simply half of their measured median figures presented in In the 100% battery-supported eCooking scenarios, the techno-economic model sizes the battery to meet the median daily cooking load found from the cooking diaries analysis for that country. In hybrid AC/DC systems, it is sized to 1/3 of this value. It is assumed that in the latter, 50% of the cooking load is battery-supported and 50% direct AC, but that cooks would be willing to cook with energy-efficient appliances, using the battery, during blackouts. On the majority of days, the modelled eCooking devices in the 100% electric scenarios would therefore have sufficient capacity to meet all of that day's cooking demand. On the days when cooking demand is higher, for example on special occasions where many guests are received, fuel stacking is assumed to occur. The costs of traditional fuels to cover this fuel stacking have been assumed to be negligible in the 100% electric scenarios, as participants in the cooking diaries studies recorded negligible traditional fuel use during the 100% electric cooking phase. However, they are fully costed in the 50% electric cooking scenarios.

Table 11, since half of the cooking by frequency is still being done on them, which is assumed to be directly proportional to energy. Further discussion of this demand analysis is available in the Kenya cooking diaries

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working paper at https://www.mecs.org.uk/working-papers/ and in the MECS/ESMAP electric cooking report (forthcoming).

Table 10: Measured energy consumption for 100% electric cooking on a mixture of inefficient and efficient appliances and modelled energy consumption for 50% electric cooking on EPCs (assuming other 50% met by baseline fuels).
N = number of days of data using only that fuel; Median daily energy per HH = Median daily energy consumption (kWh or MJ /household/day); Household size = Household members cooked for (mean of means)

	100% electricity (measured)				Proportion of energy consumed by EPC cooking 50% of meals (modelled)	
	n	Median daily energy per HH	Mean HH size	Median daily per capita energy	Median daily energy per HH	Median daily per capita energy
Kenya	431	1.4 kWh (5.1 MJ)	3.1	0.46 kWh (1.65 MJ)	0.47 kWh	0.15 kWh
Myanmar	476	1.02 kWh (3.7 MJ)	4	0.26 kWh (0.93 MJ)	0.34 kWh	0.09 kWh
Tanzania	423	2.06 kWh (7.4 MJ)	4.2	0.49 kWh (1.76 MJ)	0.69 kWh	0.16 kWh
Zambia	99	1.63 kWh (5.9 MJ)	7.9	0.21 kWh (0.75 MJ)	0.55 kWh	0.07 kWh

In the 100% battery-supported eCooking scenarios, the techno-economic model sizes the battery to meet the median daily cooking load found from the cooking diaries analysis for that country. In hybrid AC/DC systems, it is sized to 1/3 of this value. It is assumed that in the latter, 50% of the cooking load is battery-supported and 50% direct AC, but that cooks would be willing to cook with energy-efficient appliances, using the battery, during blackouts. On the majority of days, the modelled eCooking devices in the 100% electric scenarios would therefore have sufficient capacity to meet all of that day's cooking demand. On the days when cooking demand is higher, for example on special occasions where many guests are received, fuel stacking is assumed to occur. The costs of traditional fuels to cover this fuel stacking have been assumed to be negligible in the 100% electric scenarios, as participants in the cooking diaries studies recorded negligible traditional fuel use during the 100% electric cooking phase. However, they are fully costed in the 50% electric cooking scenarios.

Table 11: Measured and modelled energy consumption for 100% cooking on individual baseline fuels.
N = number of days of data using only that fuel; Median daily energy per HH = Median daily energy consumption (MJ/household/day); Household size = Household members cooked for (mean of means)

	Firewood				Charcoal				Kerosene				LPG			
	n	Median daily energy per HH (MJ)	HH size	Median daily per capita energy (MJ)	n	Median daily energy per HH (MJ)	HH size	Median daily per capita energy (MJ)	n	Median daily energy per HH (MJ)	HH size	Median daily per capita energy (MJ)	n	Median daily energy per HH (MJ)	HH size	Median daily per capita energy (MJ)

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Kenya									17	10	4	2.50	129	8.1	3.2	2.53
Myanmar	62	23.9	4.2	5.69	26	32.1	5.9	5.44					26	7.2	3.3	2.18
Tanzania					31	80.4	6.1	13.18					109	14.8	4.1	3.61
Zambia					71	49.3	6.3	7.83								

In the 50% EPC cooking scenarios, the modelled values for the electricity consumed by an EPC cooking 50% of meals are paired with half the value from the baseline fuel of interest in In the 100% battery-supported eCooking scenarios, the techno-economic model sizes the battery to meet the median daily cooking load found from the cooking diaries analysis for that country. In hybrid AC/DC systems, it is sized to 1/3 of this value. It is assumed that in the latter, 50% of the cooking load is battery-supported and 50% direct AC, but that cooks would be willing to cook with energy-efficient appliances, using the battery, during blackouts. On the majority of days, the modelled eCooking devices in the 100% electric scenarios would therefore have sufficient capacity to meet all of that day's cooking demand. On the days when cooking demand is higher, for example on special occasions where many guests are received, fuel stacking is assumed to occur. The costs of traditional fuels to cover this fuel stacking have been assumed to be negligible in the 100% electric scenarios, as participants in the cooking diaries studies recorded negligible traditional fuel use during the 100% electric cooking phase. However, they are fully costed in the 50% electric cooking scenarios.

Table 11. From a cook's perspective, most baseline stoves are similar to hotplates, as they simply heat an uninsulated pot from below. Therefore it is assumed that the proportion and type of dishes that cooks choose to cook on baseline fuels when fuel stacked with an efficient electric device such as an EPC is similar what they chose to cook on hotplates during the cooking diaries study. Therefore, the energy demand for the 50% of dishes that users choose to cook on baseline fuels is approximately 50% of the total energy recorded when 100% of dishes were cooked on the baseline fuel.

A household is modelled as comprising 4.2 people, reflecting the average size seen for the electric cooking data in the cooking diaries. The charcoal, LPG, firewood, kerosene and electricity energy use data for each country relate to households of different sizes, so are scaled linearly from the median per capita energy values.

3.3.3 Technology performance and cost assumptions

The MECS/ESMAP report presents a comparison between 2020 and 2025, with two main differences: reducing costs for eCook through technical and organisational learning; and an assumption of increasing

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charcoal, LPG, firewood and kerosene prices. Some simple parameter value uncertainty has been included in the analysis, reflecting more optimistic or pessimistic outlooks for the key variables in performance and cost, following the eCook model's approach outlined in section 2.10. Table 12 shows the assumptions, most of which were discussed in section 2.10.2. Fuel prices reflect results obtained from household surveys carried out alongside the cooking diary studies in 2017-2019, plus an assumption of 3% price increase per annum thereafter. A high/low range is then applied around these values by adding/subtracting one third.

Table 12: Parameter values used for the high and low cost scenarios for eCooking systems. All financial values are in 2018 USD prices.

	2020		2025	
Parameter	**Low cost value**	**High cost value**	**Low cost value**	**High cost value**
Battery price (Li-ion, $/kWh)	280	350	180	220
Battery min depth pf charge	10%	20%	10%	20%
Battery life (cycles)	3000	2000	3000	2000
PV-battery roundtrip efficiency	90%	85%	90%	85%
Fuel prices	2/3 of 2018[1] mean value	4/3 of 2018 mean value	2018 low value + 3%/year	2018 high value + 3%/year

The business models and financing horizons assessed follow the alternatives discussed in section 2.8. The costs of eCook are calculated for repayment over the full 20 year lifetime – representing an energy-service or utility-financing approach and for a financing period of 5 years, representing a lease-to-own or pay-as-you-go business model. For the latter all capital costs are recovered over 5 years (including a 9.6% real discount rate).

3.3.4 Summary of results

The following presents some of the overall results for this analysis, and high level conclusions, for each of the five cases. Further detail can be found in the MECS/ESMAP electric cooking report, forthcoming, including sensitivity analysis to key uncertainties.

3.3.4.1 Kenya (grid connected)

The first case study explores an opportunity for East Africans to transition completely away from biomass by fuel stacking LPG with an EPC (Figure 14). LPG is currently the aspirational fuel across most of East Africa, however, many households with an LPG stove will still purchase charcoal to cook 'heavy foods'

[1] Some values from late 2017 or early 2019.

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such as tripe, as they believe that it is cheaper. In Nairobi, fuel stacking with electricity decreases the cost of cooking for both charcoal and kerosene users. In 2020, stacking LPG with efficient electric cooking appliances already competes with using LPG alone; by 2025 the predicted rise in LPG prices means that stacking LPG with electricity is likely to become the cheapest option of all.

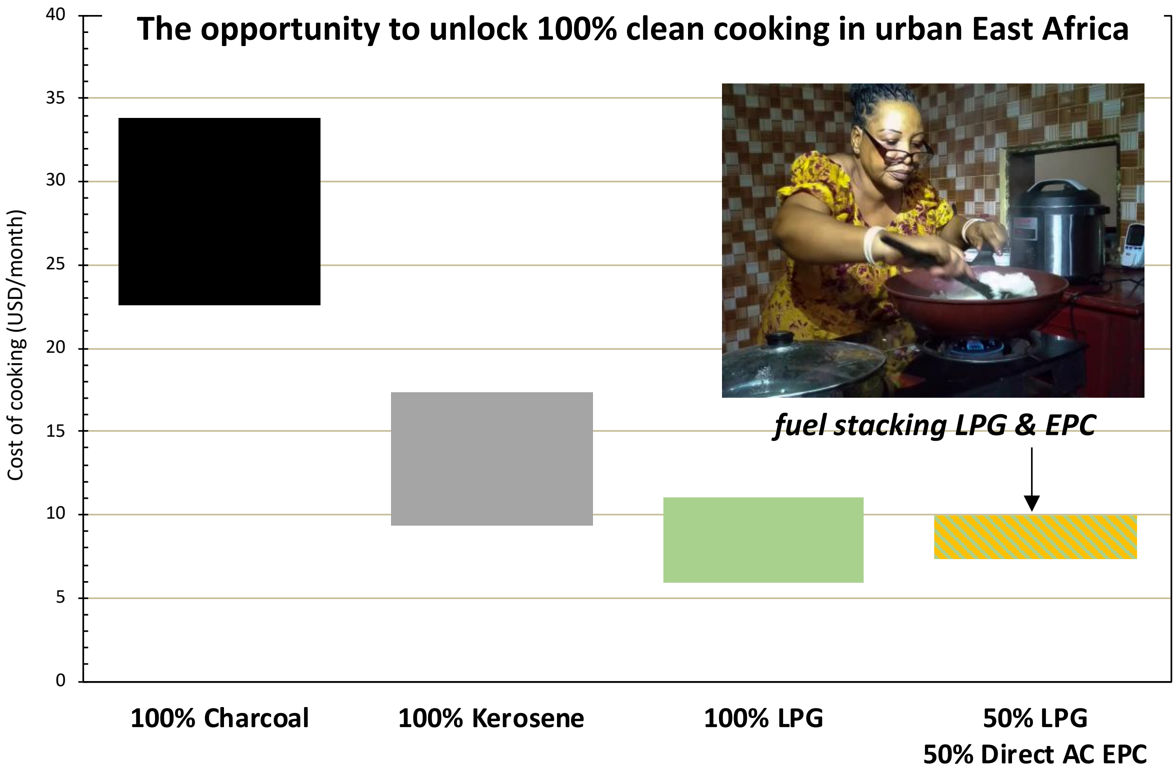

Figure 14: Selected modelling results for KPLC national grid in Nairobi, Kenya in 2020 with a 5 year financing horizon.

The results of the first case study clearly show that in urban contexts with relatively high traditional fuel prices and moderate electricity prices, both direct AC and battery-supported eCooking can already offer considerable cost savings. Of course, they will only become more competitive if, as expected, more polluting fuel prices continue to increase over time.

3.3.4.2 Zambia

This modelling case study explores the opportunity for the utility ZESCO, which has a significant customer base already cooking on electricity, to optimise the loading on their grid. Efficient eCooking appliances can significantly reduce electricity demand and peak loading for households currently cooking on inefficient appliances, such as hotplates. Furthermore, supporting eCooking appliances with a battery can

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time shift energy demand for cooking and reduce peak loading, whilst also enabling customers to cook during blackouts or load shedding.

In Zambia, electricity is already by far the cheapest option and LPG is not competitive at all (*Figure 15*). Battery-supported cooking is already the cheapest way to mitigate load shedding in Lusaka. For blackouts of up to 4 hours per day, a battery sized to meet half the daily cooking demand (0.42kWh) could enable ZESCO's customers to cook whenever they wanted. If they were able to develop an on-bill financing mechanism to break down the high upfront cost of efficient battery-supported appliances, their poorest customers could potentially cook for just 3-5 USD/month in 2020.

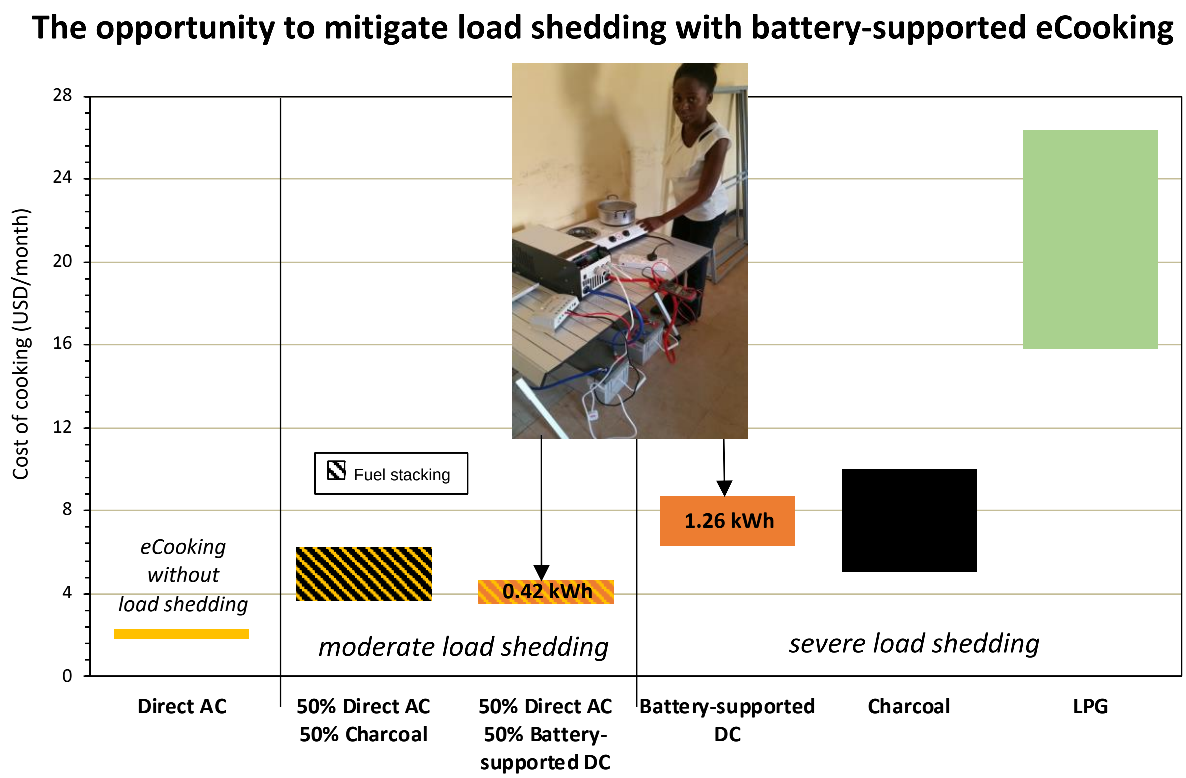

Figure 15: Selected modelling results for ZESCO national grid in Lusaka, Zambia in 2020 with a 5-year financing horizon for direct AC and 20-year financing horizon for battery-supported DC systems.

The results clearly show that in contexts with relatively low electricity tariffs, both direct AC and battery-supported eCooking can already offer considerable cost savings for charcoal users, even if charcoal is relatively cheap. In contexts with emerging LPG markets and low electricity tariffs, electricity is by far the cheapest option. Where direct AC cooking is made unworkable by unreliable grid supplies, adding in the battery does add cost, but is still less expensive than the charcoal or LPG alternatives.

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Household energy storage in the form of battery-supported eCooking systems are also an attractive proposition for users, however they may exacerbate ZESCO's problems further. Depending on how much of ZESCO's hydropower generation is run-of-the-river and how much has reservoir storage, they may well already have the ability to schedule generation at scale. If there are high levels of water storage already built into their system, it is therefore likely to be limited by energy, not peak power. Therefore, introducing more loads, even battery-supported loads, may be detrimental, as some energy is lost during the charge/discharge cycle, which may further reduce the amount of energy available on the grid. In contrast, if the system is power limited, adding battery-storage can help with reducing peak demand by time-shifting electricity demand for cooking.

3.3.4.3 Myanmar

Cooking on mini-grids is not a new idea – it's already happening in many South and Southeast Asian countries. Rice is the major staple across much of the region and electric rice cookers are both very easy to use and energy-efficient. The abundance of hydropower resources has enabled the establishment of mini-grids with very low unit costs. However, with the rapidly falling prices of batteries and solar PV, new opportunities are opening up for the integration of energy-efficient eCooking in a broader range of systems, in particular solar and solar/diesel hybrid mini-grids, and for electricity to be used for a greater proportion of the day's cooking.

Peak loading is a major concern for electric cooking on power-limited mini-grids, but a variety of time-shifting techniques can decouple electricity demand from supply, smoothing out the load profile and bringing down the Levelised Cost of Electricity (LCoE). These include centralised or decentralised battery storage, smart metering, distributed load control and collaborative agreements.

This case study of a micro-hydro mini-grid in Shan State highlights the opportunity for mini-grid developers who have already enabled cooking on their systems, to allow their customers to do all of their cooking with electricity (Figure 16). At peak times, the grid reaches capacity and the voltage dips, however, the users agreed to only cook with electricity when the voltage is high enough (indicated by a voltmeter installed by the mini-grid developer in every kitchen). Supporting the entire cooking load with a battery would not be cost effective versus purchased firewood, however it is also not necessary. A battery is only required when the grid is overloaded, therefore a much smaller (and cheaper) battery can still enable 100% eCooking. This is already cost competitive with LPG in 2020 and by 2025 is also projected to be cost-comparable with firewood. In fact, by 2025, even supporting the whole day's cooking with a battery becomes cost effective with tariffs below 0.13 USD/kWh. For other mini-grids with spare capacity at peak

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times in communities with similar firewood prices, direct AC eCooking is already cheaper than stacking firewood/electricity with tariffs below 0.20 USD/kWh in 2020.

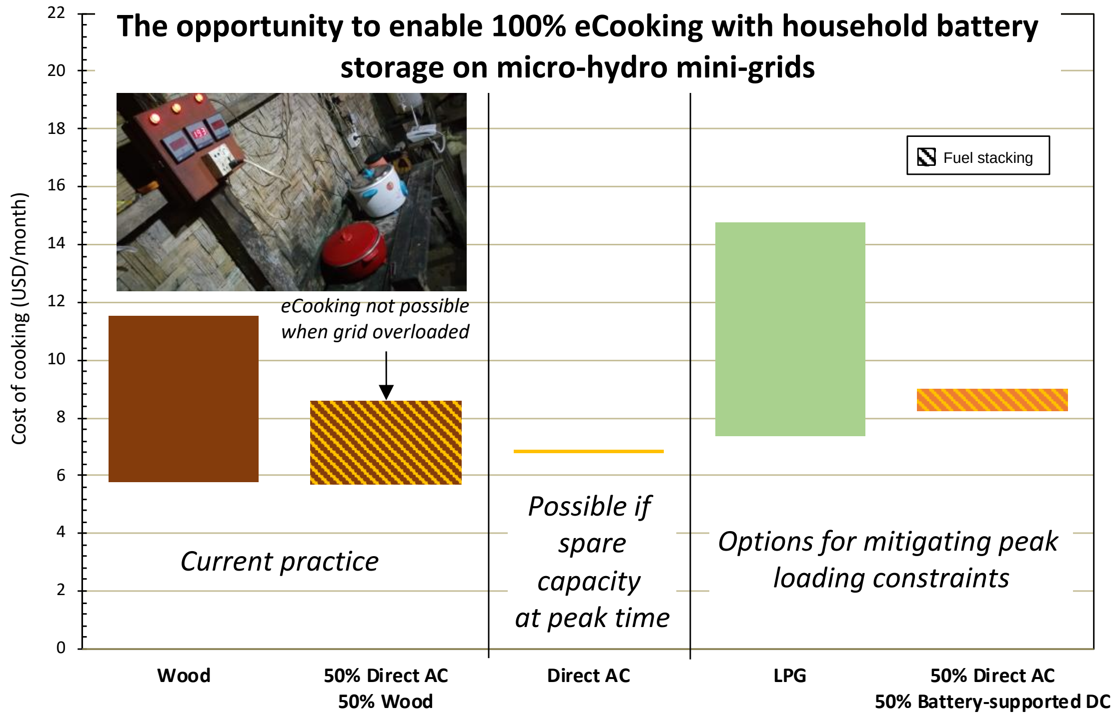

Figure 16: Selected modelling results for micro-hydro mini-grid in Naung Pain Lay, Pyin Oo Lwin, Myanmar, with 5 year financing horizon for direct AC and 20 year for battery-supported DC systems.

3.3.4.4 Tanzania

This case study explores thee opportunities for electric cooking connected to TaTEDO's solar/biomass hybrid mini-grid in Kibindu. The case represents what could be the lowest hanging fruit, that is likely to be the first step for eCooking in the most adversarial contexts, where the cost of electricity is high, yet biomass fuels are available at a very low cost (Figure 17). It focusses in on the most efficient appliance, the EPC, and combines it with the most energy-efficient practices to create an ultra-efficient eCooking solution targeted at the foods that are most energy-intensive foods: 'heavy foods'. The case study results show that for a micro-business pre-cooking 500g beans per day, an EPC is already cost comparable with charcoal, despite the extremely high tariff of 1.35 USD/kWh. LPG is by far the most expensive option. However, the mini-grid tariff is so high that the most cost-effective solution would in fact be to create a standalone solar eCooking system sized for a single load in the EPC each day. This is already cost effective in 2020 under a private sector lease to own business model with a 5-year repayment horizon.

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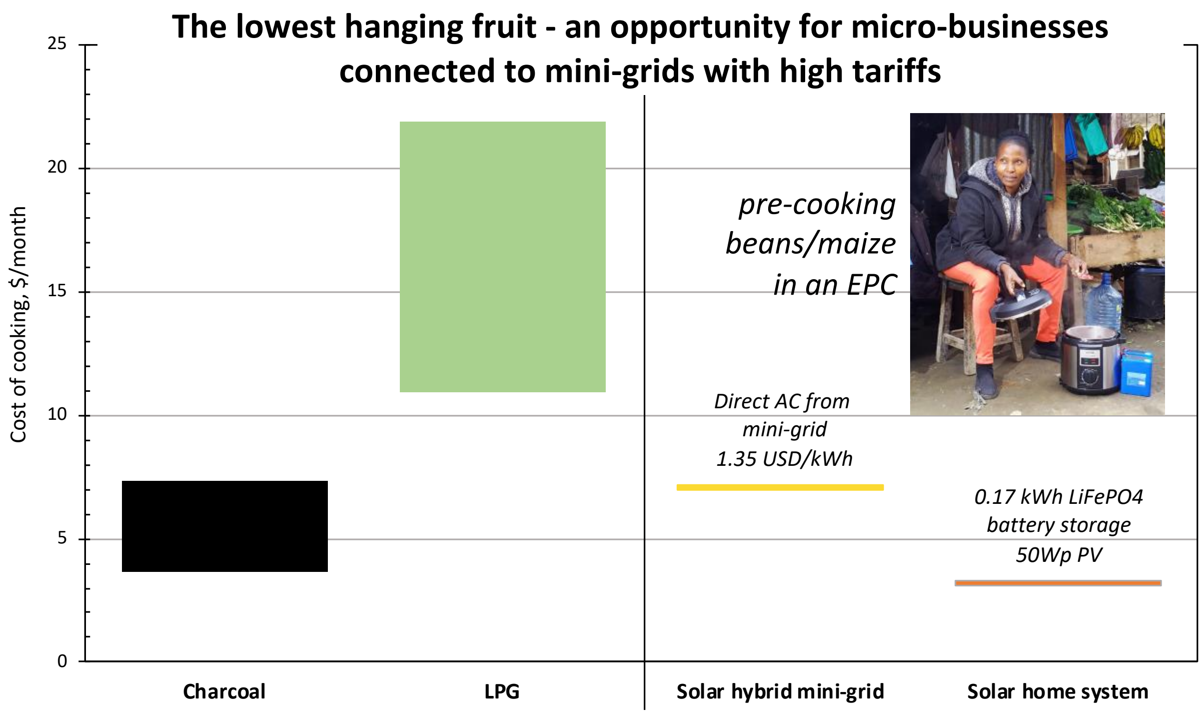

Figure 17: Selected modelling results for solar-biomass hybrid mini-grid Kibindu, Tanzania, with 5-year financing horizon for direct AC and 20 year for solar battery-supported DC systems.

3.3.4.5 Kenya (off-grid)

The final case study focusses on a Kenyan village, where cooking was previously dominated by firewood, but dwindling supplies and increasing livelihood opportunities have led many to adopt commercialized, polluting fuels such as charcoal and kerosene (Figure 18). Pairing a standalone solar electric cooking appliance with high performance battery storage and a suitably sized solar panel can enable cost-effective off-grid eCooking. Until recently, such a device would have been unrealistically expensive for families across the developing world. However, continued reductions in the price of the two main cost components, PV and batteries, and the development of highly efficient eCooking appliances, such as the EPC, over the last decade mean that when paired with appropriate financing models, a solar home system sized for cooking can already be cost effective in some markets.

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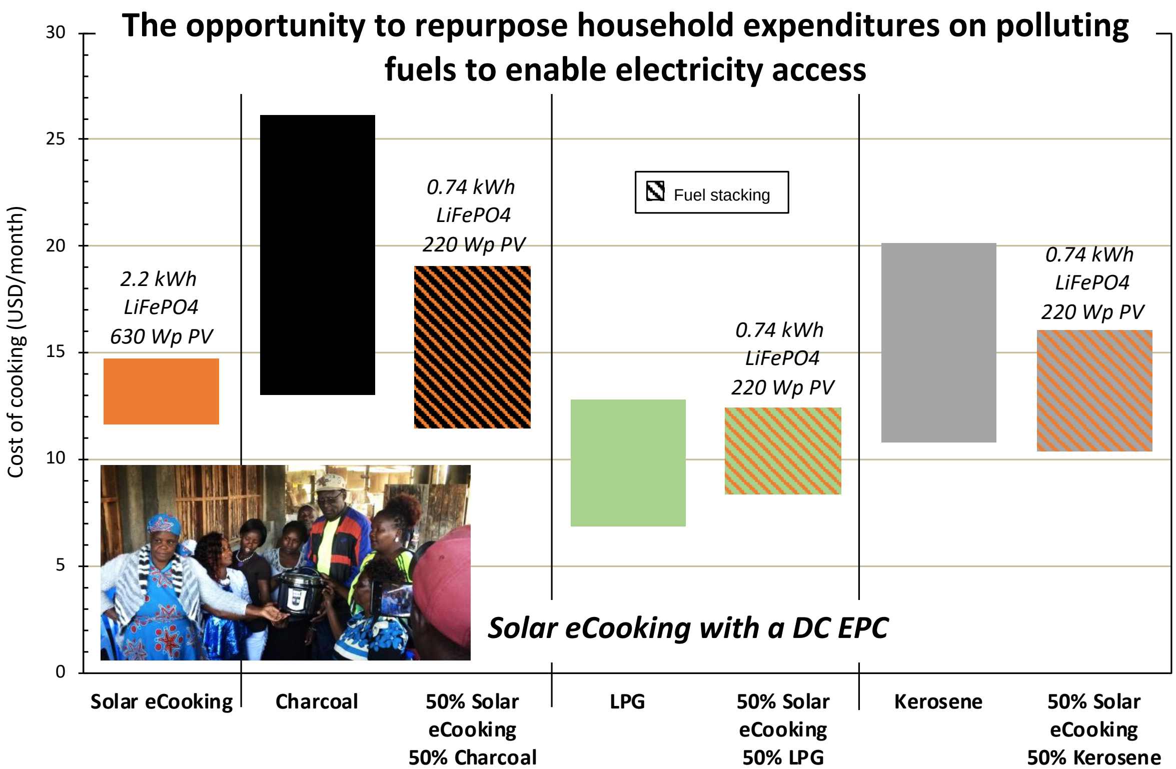

Figure 18: Selected modelling results for solar eCooking in Echariria, Nakuru County, Kenya, with 20 year financing horizon on solar powered battery-supported DC appliances.

Rapid urbanisation in many parts of the Global South is forcing many of those who collect wood to start paying for it, and for those who already pay, to pay higher prices. Urban centres generally have higher charcoal prices than peri-urban and rural areas, where solar electric cooking solutions are likely to be most valuable. In rural areas, households may not even pay at all for their fuel. However, in places where cooking is gradually being monetised, it creates an opportunity for these people to divert that expenditure on biomass fuels into repayments on a solar electric cooking system.

The case study results show that in this context, high charcoal prices already make solar electric cooking cost effective. The cheapest option is currently LPG, however stacking this with a battery-supported solar-powered DC EPC does not significantly increase the cost and yields important co-benefits. By 2025, fuel stacking LPG with a DC EPC is cost comparable with cooking all food on LPG, meaning that the energy services enabled by solar home systems are essentially available for free. This is likely to be a key purchasing trigger, as it offers something to everyone in the household, not just the cook. These services are highly valued, as hundreds of thousands of Kenyan households have already signed up for PAYG (pay as you go) solar lighting systems and frequently pay in excess of 10 USD/month just to be able to use these low power appliances.

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This shows that eCooking is no longer constrained by the limits of electricity grids. The solar revolution that has enabled access to low power energy services, in particular lighting, is now ready to take its next step up and enable eCooking for Africa's vast off-grid population. The LED made solar lighting systems affordable by reducing energy demand by an order of magnitude – it seems that the EPC in particular has an equally transformative potential for solar eCooking.

3.3.5 Overall conclusions on MECS/ESMAP modelling

There has been a widespread perception that electricity is too expensive for cooking in developing regions. Through detailed analysis of five diverse contexts, the analysis shows that this is no longer true. With appropriate support, electric cooking will gain increasing commercial and political interest. Enabling the transition to eCooking will bring about environmental, gender and health benefits to some of the world's most disadvantaged people.

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4 Conclusions

This paper provides an overview of the eCook model: its origins, structure and approach, key data and assumptions, and overviews of the applications it has been used for to date. To avoid replication, reference is made to other papers where further detail or more extensive discussion of particular aspects can be found.

The model is one of the tools deployed within the MECS programme, supporting analysis of technologies and clean cooking applications. The workplan includes:

(a) Analyse and/or evaluate eCook system options proposed (from within the MECS team, or externally), with direct outputs and as inputs to LCA and MCDA frameworks
(b) Contribute to eCook system design, in terms of component choice and sizing
(c) Further develop and refine the eCook model itself, as a contribution to knowledge and as a tool for wider application.

The objectives set for model improvement over the course of MECS relate to: the detail in representation of cooking practices; the functionality of the eCook model itself; and the integration of the model with the wider research frameworks. The key developments anticipated are:

- Cooking model and eCook model taken down to the hourly level for individual households: allowing representation of the temporal variation in cooking energy use within a day, and of the implications for battery use and system generally
- Cooking model and eCook model developed to represent a community of households, potentially connected to a minigrid; link the eCook model to microgrid models being developed or adopted in other parts of MECS
- Develop and integrate Monte-Carlo methods to represent the parameter value uncertainty with improved rigour.
- Link the eCook model as an input to the Multi-Criteria Decision Analysis framework and Life Cycle Assessment framework being developed within MECS

The application and ongoing development of the eCook model will help build a more complete picture of the opportunities and challenges that await this emerging concept. Further outputs will be available from https://elstove.com/innovate-reports/ and https://www.mecs.org.uk/.

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6 Appendix

6.1 Appendix A: Problem statement and background to Innovate eCook project

6.1.1 Beyond business as usual

The use of biomass and solid fuels for cooking is the everyday experience of nearly 3 Billion people. This pervasive use of solid fuels—including wood, coal, straw, and dung—and traditional cookstoves results in high levels of household air pollution, extensive daily drudgery required to collect fuels, and serious health impacts. It is well known that open fires and primitive stoves are inefficient ways of converting energy into heat for cooking. The average amount of biomass cooking fuel used by a typical family can be as high as two tons per year. Indoor biomass cooking smoke also is associated with a number of diseases, including acute respiratory illnesses, cataracts, heart disease and even cancer. Women and children in particular are exposed to indoor cooking smoke in the form of small particulates up to 20 times higher than the maximum recommended levels of the World Health Organization. It is estimated that smoke from cooking fuels accounts for nearly 4 million premature deaths annually worldwide –more than the deaths from malaria and tuberculosis combined.

While there has been considerable investment in improving the use of energy for cooking, the emphasis so far has been on improving the energy conversion efficiency of biomass. Indeed in a recent overview of the state of the art in Improved Cookstoves (ICS), ESMAP & GACC (2015), World Bank (2014), note that the use of biomass for cooking is likely to continue to dominate through to 2030.

> "Consider, for a moment, the simple act of cooking. Imagine if we could change the way nearly five hundred million families cook their food each day. It could slow climate change, drive gender equality, and reduce poverty. The health benefits would be enormous." ESMAP & GACC (2015)

The main report goes on to say that "The "business-as-usual" scenario for the sector is encouraging but will fall far short of potential." (ibid,) It notes that without major new interventions, over 180 million households globally will gain access to, at least, minimally improved[2] cooking solutions by the end of the decade. However, they state that this business-as-usual scenario will still leave over one- half (57%) of the

[2] A minimally improved stove does not significantly change the health impacts of kitchen emissions. "For biomass cooking, pending further evidence from the field, significant health benefits are possible only with the highest quality fan gasifier stoves; more moderate health impacts may be realized with natural draft gasifiers and vented intermediate ICS" (ibid)

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developing world's population without access to clean cooking in 2020, and 38% without even minimally improved cooking solutions. The report also states that 'cleaner' stoves are barely affecting the health issues, and that only those with forced gasification make a significant improvement to health. Against this backdrop, there is a need for a different approach aimed at accelerating the uptake of truly 'clean' cooking.

Even though improved cooking solutions are expected to reach an increasing proportion of the poor, the absolute numbers of people without access to even 'cleaner' energy, let alone 'clean' energy, will increase due to population growth. The new Sustainable Development Goal 7 calls for the world to "ensure access to affordable, reliable, sustainable and modern energy for all". Modern energy (electricity or LPG) would indeed be 'clean' energy for cooking, with virtually no kitchen emissions (other than those from the pot). However, in the past, modern energy has tended to mean access to electricity (mainly light) and cooking was often left off the agenda for sustainable energy for all.

Even in relation to electricity access, key papers emphasise the need for a step change in investment finance, a change from 'business as usual'. IEG World Bank Group (2015) note that 22 countries in the Africa Region have less than 25 percent access, and of those, 7 have less than 10 percent access. Their tone is pessimistic in line with much of the recent literature on access to modern energy, albeit in contrast to the stated SDG7. They discuss how population growth is likely to outstrip new supplies and they argue that "unless there is a big break from recent trends the population without electricity access in Sub-Saharan Africa is projected to increase by 58 percent, from 591 million in 2010 to 935 million in 2030." They lament that about 40% of Sub-Saharan Africa's population is under 14 years old and conclude that if the current level of investment in access continues, yet another generation of children will be denied the benefits of modern service delivery facilitated by the provision of electricity (IEG World Bank Group, 2015).

> "Achieving universal access within 15 years for the low-access countries (those with under 50 percent coverage) requires a quantum leap from their present pace of 1.6 million connections per year to 14.6 million per year until 2030." (ibid)

Once again, the language is a call for a something other than business as usual. The World Bank conceives of this as a step change in investment. It estimates that the investment needed to really address global electricity access targets would be about $37 billion per year, including erasing generation deficits and additional electrical infrastructure to meet demand from economic growth. "By comparison, in recent years, low-access countries received an average of $3.6 billion per year for their electricity sectors from public and private sources" (ibid). The document calls for the Bank Group's energy practice to adopt a

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new and transformative strategy to help country clients orchestrate a national, sustained, sector-level engagement for universal access.

In the following paragraphs, we explore how increasing access to electricity could include the use of solar electric cooking systems, meeting the needs of both supplying electricity and clean cooking to a number of households in developing countries with sufficient income.

6.1.2 Building on previous research

Gamos first noted the trends in PV and battery prices in May 2013. We asked ourselves the question, is it now cost effective to cook with solar photovoltaics? The answer in 2013 was 'no', but the trends suggested that by 2020 the answer would be yes. We published a concept note and started to present the idea to industry and government. Considerable interest was shown but uncertainty about the cost model held back significant support. Gamos has since used its own funds to undertake many of the activities, as well as IP protection (a defensive patent application has been made for the battery/cooker combination) with the intention is to make all learning and technology developed in this project open access, and awareness raising amongst the electrification and clean cooking communities (e.g. creation of the infographic shown in Figure 19 to communicate the concept quickly to busy research and policy actors).

Gamos has made a number of strategic alliances, in particular with the University of Surrey (the Centre for Environmental Strategy) and Loughborough University Department of Geography and seat of the Low Carbon Energy for Development Network). In October 2015, DFID commissioned these actors to explore assumptions surrounding solar electric cooking[3] (Batchelor, 2015b; Brown and Sumanik-Leary, 2015; Leach and Oduro, 2015; Slade, 2015). The commission arose from discussions between consortium members, DFID, and a number of other entities with an interest in technological options for cleaner cooking e.g. Shell Foundation and the Global Alliance for Clean Cookstoves.

Drawing on evidence from the literature, the papers show that the concept is technically feasible and could increase household access to a clean and reliable modern source of energy. Using a bespoke economic model, the Leach and Oduro paper also confirm that by 2020 a solar based cooking system could be comparable in terms of monthly repayments to the most common alternative fuels, charcoal and LPG. Drawing on published and grey literatures, many variables were considered (e.g. cooking energy needs, technology performance, component costs). There is uncertainty in many of the parameter values, including in the assumptions about future cost reductions for PV and batteries, but the cost ranges for the

[3] The project has been commissioned through the PEAKS framework agreement held by DAI Europe Ltd.

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solar system and for the alternatives overlap considerably. The model includes both a conservative 5% discount rate representing government and donor involvement, and a 25% discount rate representing a private sector led initiative with a viable return. In both cases, the solar system shows cost effectiveness in 2020.

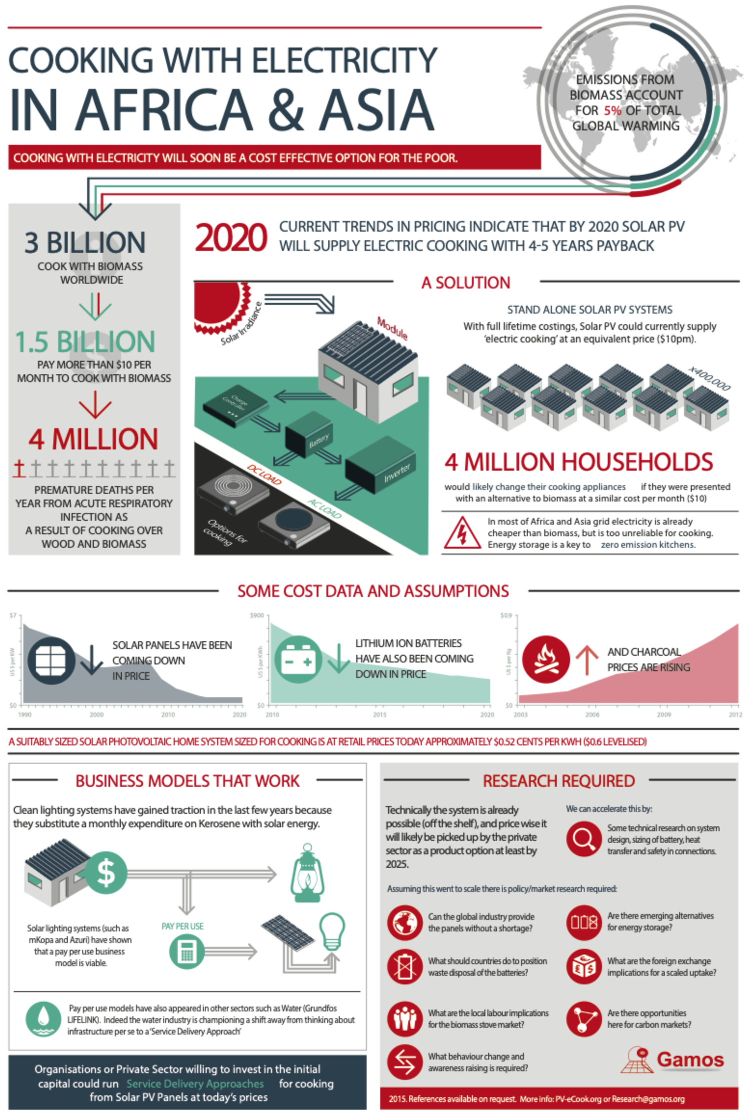

Figure 19 Infographic summarising the concept in order to lobby research and policy actors.

The Brown and Sumanik-Leary paper in the series examines the lessons learned from four transitions – the uptake of electric cooking in South Africa, the roll out of Improved Cookstoves (ICS), the use of LPG and the uptake of Solar Home Systems (SHS). They present many behavioural concerns, none of which preclude the proposition as such, but all of which suggest that any action to create a scaled use of solar

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electric cooking would need in depth market analysis; products that are modular and paired with locally appropriate appliances; the creation of new, or upgrading of existing, service networks; consumer awareness raising; and room for participatory development of the products and associated equipment.

A synthesis paper summarising the above concludes by emphasising that the proposition is not a single product – it is a new genre of action and is potentially transformative. Whether solar energy is utilised within household systems or as part of a mini, micro or nano grid, linking descending solar PV and battery costs with the role of cooking in African households (and the Global South more broadly) creates a significant potential contribution to SDG7. Cooking is a major expenditure of 500 million households. It is a major consumer of time and health. Where households pay for their fuelwood and charcoal (approximately 300 Million) this is a significant cash expense. Solar electric cooking holds the potential to turn this (fuelwood and charcoal) cash into investment in modern energy. This “consumer expenditure” is of an order of magnitude more than current investment in modern energy in Africa and to harness it might fulfil the calls for a step change in investment in electrical infrastructure.

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6.2 Summary of related projects

A series of inter-related projects have led to and will follow on from the research presented in this report:

- Gamos Ltd.'s early conceptual work on eCook (Batchelor, 2013).
    - The key **CONCEPT NOTE** can be found here.
    - An early infographic and a 2018 infographic can be found here.
- Initial technical, economic and behavioural feasibility studies on eCook commissioned by DfID (UK Aid) through the CEIL-PEAKS Evidence on Demand service and implemented by Gamos Ltd., Loughborough University and University of Surrey.
    - The key **FINAL REPORTS** can be found here.
- Conceptual development, stakeholder engagement & prototyping in Kenya & Bangladesh during the "*Low cost energy-efficient products for the bottom of the pyramid*" project from the USES programme funded by DfID (UK Aid), EPSRC & DECC (now part of BEIS) & implemented by University of Sussex, Gamos Ltd., ACTS (Kenya), ITT & UIU (Bangladesh).
    - The key **PRELIMINARY RESULTS** (Q1 2019) can be found here.
- A series of global & local market assessments in Myanmar, Zambia and Tanzania under the "*eCook - a transformational household solar battery-electric cooker for poverty alleviation*" project funded by DfID (UK Aid) & Gamos Ltd. through Innovate UK's Energy Catalyst Round 4, implemented by Loughborough University, University of Surrey, Gamos Ltd., REAM (Myanmar), CEEEZ (Zambia) & TaTEDO (Tanzania).
    - The key **PRELIMINARY RESULTS** (Q1 2019) can be found here.
- At time of publication (Q4 2019), a new DfID (UK Aid) funded research programme '*Modern Energy Cooking Services*' (MECS) lead by Prof. Ed Brown at Loughborough University has just completed the first of five years and will take forward these ideas & collaborations.

This data and material have been funded by UK AID from the UK government; however, the views expressed do not necessarily reflect the UK government's official policies.

6.3 About the Modern Energy Cooking Services (MECS) Programme.

Sparking a cooking revolution: catalysing Africa's transition to clean electric/gas cooking.

www.mecs.org.uk | mecs@lboro.ac.uk

Modern Energy Cooking Services (MECS) is a five-year research and innovation programme funded by UK Aid (DFID). MECS hopes to leverage investment in renewable energies (both grid and off-grid) to address the clean cooking challenge by integrating modern energy cooking services into the planning for access to affordable, reliable and sustainable electricity.

Existing strategies are struggling to solve the problem of unsustainable, unhealthy but enduring cooking practices which place a particular burden on women. After decades of investments in improving biomass cooking, focused largely on increasing the efficiency of biomass use in domestic stoves, the technologies developed are said to have had limited impact on development outcomes. The Modern Energy Cooking Services (MECS) programme aims to break out of this "business-as-usual" cycle by investigating how to rapidly accelerate a transition from biomass to genuinely 'clean' cooking (i.e. with electricity or gas).

Worldwide, nearly three billion people rely on traditional solid fuels (such as wood or coal) and technologies for cooking and heating[4]. This has severe implications for health, gender relations, economic livelihoods, environmental quality and global and local climates. According to the World Health Organization (WHO), household air pollution from cooking with traditional solid fuels causes to 3.8 million premature deaths every year – more than HIV, malaria and tuberculosis combined[5]. Women and children are disproportionally affected by health impacts and bear much of the burden of collecting firewood or other traditional fuels.

Greenhouse gas emissions from non-renewable wood fuels alone total a gigaton of CO_2e per year (1.9-2.3% of global emissions)[6]. The short-lived climate pollutant black carbon, which results from incomplete combustion, is estimated to contribute the equivalent of 25 to 50 percent of carbon dioxide warming globally – residential solid fuel burning accounts for up to 25 percent of global black carbon emissions[7].

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[4] http://www.who.int/indoorair/health_impacts/he_database/en/

[5] https://www.who.int/en/news-room/fact-sheets/detail/household-air-pollution-and-health https://www.who.int/gho/hiv/epidemic_status/deaths_text/en/, https://www.who.int/en/news-room/fact-sheets/detail/malaria, https://www.who.int/en/news-room/fact-sheets/detail/tuberculosis

[6] Nature Climate Change 5, 266–272 (2015) doi:10.1038/nclimate2491

[7] http://cleancookstoves.org/impact-areas/environment/

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Up to 34% of woodfuel harvested is unsustainable, contributing to climate change and local forest degradation. In addition, approximately 275 million people live in woodfuel depletion 'hotspots' – concentrated in South Asia and East Africa – where most demand is unsustainable[8].

Africa's cities are growing – another Nigeria will be added to the continent's total urban population by 2025[9] which is set to double in size over the next 25 years, reaching 1 billion people by 2040. Within urban and peri-urban locations, much of Sub Saharan Africa continues to use purchased traditional biomass and kerosene for their cooking. Liquid Petroleum Gas (LPG) has achieved some penetration within urban conurbations, however, the supply chain is often weak resulting in strategies of fuel stacking with traditional fuels. Even where electricity is used for lighting and other amenities, it is rarely used for cooking (with the exception of South Africa). The same is true for parts of Asia and Latin America. Global commitments to rapidly increasing access to reliable and quality modern energy need to much more explicitly include cooking services or else household and localized pollution will continue to significantly erode the well-being of communities.

Where traditional biomass fuels are used, either collected in rural areas or purchased in peri urban and urban conurbations, they are a significant economic burden on households either in the form of time or expenditure. The McKinsey Global Institute outlines that much of women's unpaid work hours are spent on fuel collection and cooking[10]. The report shows that if the global gender gap embodied in such activities were to be closed, as much as $28 trillion, or 26 percent, could be added to the global annual GDP in 2025. Access to modern energy services for cooking could redress some of this imbalance by releasing women's time into the labour market.

To address this global issue and increase access to clean cooking services on a large scale, investment needs are estimated to be at least US$4.4 billion annually[11]. Despite some improvements in recent years, this cross-cutting sector continues to struggle to reach scale and remains the least likely SE4All target to

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[8] Nature Climate Change 5, 266–272 (2015) doi:10.1038/nclimate2491

[9] https://openknowledge.worldbank.org/handle/10986/25896

[10] McKinsey Global Institute. *The Power of Parity: How Advancing Women's Equality can add $12 Trillion to Global Growth*; McKinsey Global Institute: New York, NY, USA, 2015.

[11] The SE4ALL Global Tracking Report shows that the investment needed for universal access to modern cooking (not including heating) by 2030 is about $4.4 billion annually. In 2012 investment was in cooking was just $0.1 billion. Progress toward Sustainable Energy: Global Tracking Report 2015, World Bank.

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be achieved by 2030[12], hindering the achievement of the UN's Sustainable Development Goal (SDG) 7 on access to affordable, reliable, sustainable and modern energy for all.

Against this backdrop, MECS draws on the UK's world-leading universities and innovators with the aim of sparking a revolution in this sector. A key driver is the cost trajectories that show that cooking with (clean, renewable) electricity has the potential to reach a price point of affordability with associated reliability and sustainability within a few years, which will open completely new possibilities and markets. Beyond the technologies, by engaging with the World Bank (ESMAP), MECS will also identify and generate evidence on other drivers for transition including understanding and optimisation of multi-fuel use (fuel stacking); cooking demand and behaviour change; and establishing the evidence base to support policy enabling environments that can underpin a pathway to scale and support well understood markets and enterprises.

The five-year programme combines creating a stronger evidence base for transitions to modern energy cooking services in DFID priority countries with socio-economic technological innovations that will drive the transition forward. It is managed as an integrated whole; however, the programme is contracted via two complementary workstream arrangements as follows:

- An Accountable Grant with Loughborough University (LU) as leader of the UK University Partnership.
- An amendment to the existing Administrative Arrangement underlying DFID's contribution to the ESMAP Trust Fund managed by the World Bank.

The intended outcome of MECS is a market-ready range of innovations (technology and business models) which lead to improved choice of affordable and reliable modern energy cooking services for consumers. Figure 20 shows how the key components of the programme fit together. We will seek to have the MECS principles adopted in the SDG 7.1 global tracking framework and hope that participating countries will incorporate modern energy cooking services in energy policies and planning.

[12] The 2017 SE4All Global Tracking Framework Report laments that, "Relative to electricity, only a small handful of countries are showing encouraging progress on access to clean cooking, most notably Indonesia, as well as Peru and Vietnam."

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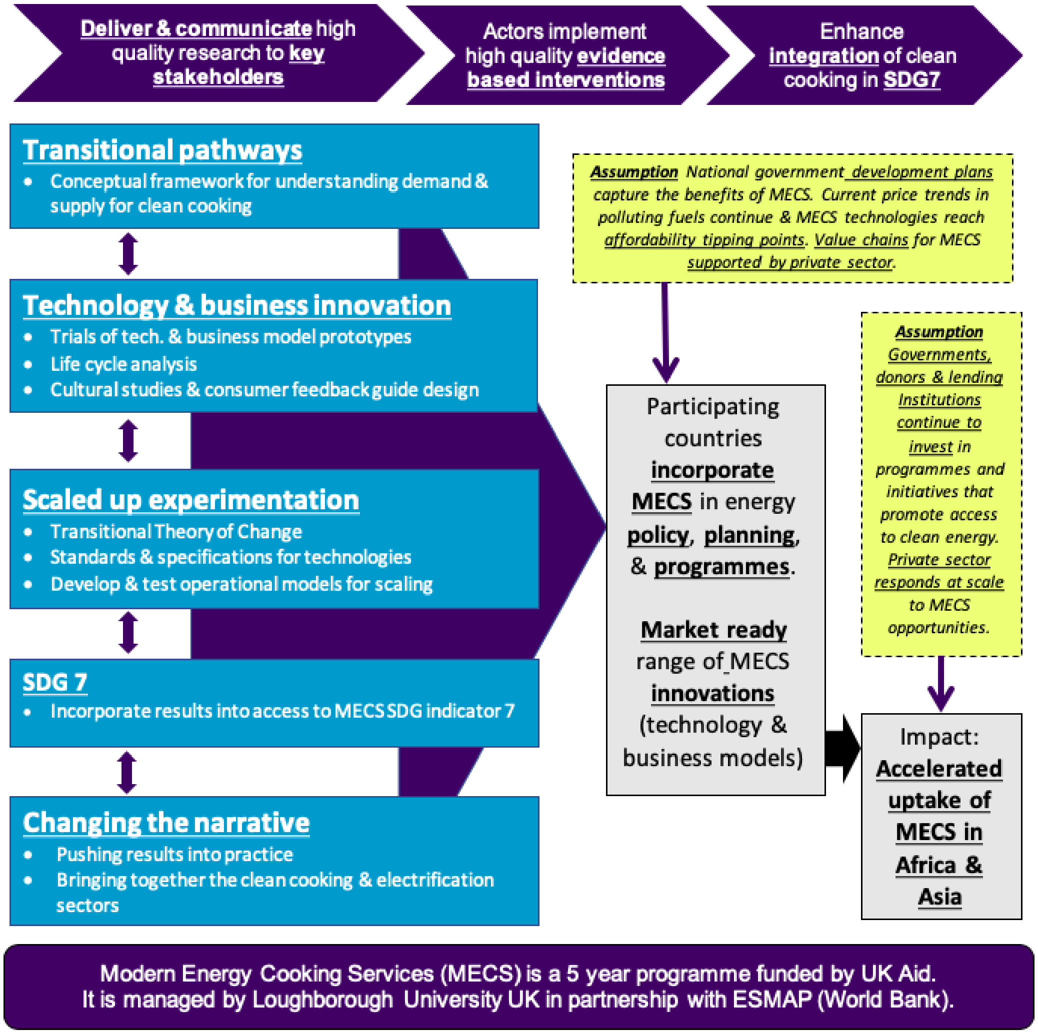

Figure 20: Overview of the MECS programme.

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