Article:

Hutty, T., Hammond, J., Roberts, D. et al. (4 more authors) (2024) Lead-acid battolysers for hydrogen cooking: a comparison with electric cooking for sub-Saharan Africa. Energy for Sustainable Development, 81. 101491. ISSN 0973-0826

https://doi.org/10.1016/j.esd.2024.101491

Lead-acid battolysers for hydrogen cooking: a comparison with electric cooking for sub-Saharan Africa

Timothy Hutty[a], Joseph Hammond[a], Diarmid Roberts[a], John Barton[b], Jonathan Wilson[b], Dani Strickland[b], Solomon Brown[a]*

[a]*Department of Chemical and Biological Engineering, University of Sheffield, UK*
[b]*CREST, Loughborough University, Loughborough, UK,*

Abstract

A battolyser combines the function of battery and electrolyser in one device, i.e. it provides both electrical energy storage and a means to produce hydrogen. A battolyser with lead-acid chemistry has recently been proposed, and this has potential as a particularly low-cost solution. Here, the battolyser is considered for the production of hydrogen as a cooking fuel ("hCooking") in sub-Saharan Africa, a region where cooking typically employs polluting fuels (firewood and charcoal). The more conventional approach for decarbonisation of cooking is the introduction of electric cookers (e.g. hotplate, induction hob, pressure cooker) which can be powered by PV and possibly battery storage; accordingly these electric cooking ("eCooking") systems are considered as the competing decarbonised technology. Multi-objective optimisation is used to design both battolyser and eCooking systems for a notional off-grid community, with solar PV as the main energy source. Objectives are the minimisation of net present cost and lifetime greenhouse gas emissions, and Pareto frontiers are produced to show the play-off between these. Results show that a battolyser system could eliminate 95.6% of CO_2 emissions when compared with a baseline using charcoal, at an annualised cost of $507 per household, over a system lifetime of 20 years. However, eCooking systems appear superior to the battolyser, with the cleanest battery + eCook system achieving 95.8% emissions reduction at annualised cost $422 / household. More generally, hCooking systems are nearly always Pareto dominated by eCooking systems, even under a realistic range of sensitivity scenarios. This result is due to the inherently higher energy intensity of cooking over a flame compared to the eCooking options. Priorities to make the battolyser a more viable solution include extending its lifetime as far as possible, cheaper PV systems, and improved hydrogen burner efficiencies. We also show that eCooking together with some continued use of charcoal may be the cheapest possible cooking solution, whilst simultaneously curtailing 60% of lifetime greenhouse gas emissions.

Keywords: battolyser; hydrogen cooking hCooking; electric cooking eCooking; sub-Saharan Africa; solar PV

*Corresponding author.
E-mail address: s.f.brown@sheffield.ac.uk

Nomenclature

Abbreviations.	
DHI	Diffuse horizontal irradiance
DNI	Direct normal irradiance
eCooking	Electric cooking
EPC	Electric pressure cooker
GHG	Greenhouse gas
GHI	Global horizontal irradiance
hCooking	Hydrogen cooking
LCA	Life cycle assessment
LHV	Lower heating value
LPG	Liquid petroleum gas
NPC	Net present cost
PV	Photovoltaic generation
SSA	sub-Saharan Africa
USD	U.S. dollar

1. Introduction

1.1 Decarbonisation of cooking for sub-Saharan Africa

Cooking in sub-Saharan Africa (SSA) often employs biomass (firewood, charcoal, dung), kerosene or coal. The smoke from these fuels is detrimental to health, with one estimate suggesting that 500 000 premature deaths are caused annually in SSA. Furthermore, the biomass fuels are not necessarily sustainably produced, contributing to greenhouse gas (GHG) emissions and deforestation [1]. There are various options for cleaner cooking technologies, of which the front-runners are arguably electric cooking (eCooking) and liquefied petroleum gas (LPG); eCooking devices include hotplate, induction hob, slow cooker and electric pressure cooker (EPC) [2], [3]. Less widespread approaches include solar cookers and biogas. This present work, meanwhile, considers an alternative approach to cleaner cooking, using hydrogen ("hCooking"); the environmental and economic merits of hCooking will be compared to the more established eCooking technology. For hCooking, a battolyser is considered for hydrogen production, functioning as both electrolyser and battery (see Section 1.2).

Previous work on cleaner cooking technologies has mainly focused on eCooking, with hCooking receiving much less consideration. The literature is generally optimistic that eCooking is cost-competitive with LPG [2], [4], [5]; cost-competitivity with wood or charcoal appears to be a possibility, although less clearcut.

One of the widest-ranging analyses of the transition to clean cooking for SSA was carried out by Leach et al [2] as part of the MECS (Modern Energy Cooking Services) programme [6]. This work encompassed modelling of load profiles, network analysis, life cycle assessment (LCA) and cost-benefit analysis, and the methodology was applied to three case studies. For an 'on-grid' location in Zambia, cheap grid electricity tariffs meant that eCooking could achieve marked savings on bills. For a pre-existing minigrid in Tanzania, eCooking was competitive with LPG on cost, and also with charcoal under some circumstances. For an off-grid location in Kenya, economics for eCooking were more challenging; however a hybrid system with a mixture of eCooking and LPG showed promise. An ESMAP report [7] reached similar conclusions, predicting that eCooking is cost-competitive with charcoal in a variety of circumstances, or would become so by 2025. eCooking in the context of a PV microgrid was also considered by Lombardi et al [5], and found to be cost-competitive with other options including LPG. Van Buskirk et al [8] considered solar powered eCooking in SSA, focusing on direct-use DC solar and lithium titanate batteries, with a view to evaluating competitivity with wood as a fuel; both systems showed a strong possibility to be cost-competitive with wood in terms of marginal levelized cost of energy. Antonanzas-Torres et al [4] considered eCooking powered by a low-powered home PV system, with results suggesting that eCooking was within the competitive price range with wood and charcoal, although to ensure reliability it should be combined with the traditional fuels, particularly in larger households. Batchelor et al [9] employed multi-criteria decision analysis to identify the nations most ripe for a transition to eCook; Southern and Eastern Africa were identified as the key regions, with Zambia, Kenya and Tanzania offering the highest viability of all.

The motivation to consider hCooking stems from hydrogen's low storage price per kWh compared to batteries, allowing for longer term storage [10]–[12]. Hydrogen may also feel more familiar to those who previously cooked on gas or liquid fuels. Nonetheless, hCooking has received little attention in the literature. Schöne et al [13] considered the potential of hydrogen for cooking in remote African communities, either used directly for hCooking, or with electrolyser + fuel cell as an electrical energy store to support eCooking. Direct use of hydrogen was found to be the more economical option in terms of annualised value. Topriska et al [14] considered solar hCooking systems to supply cooking demand in Ghana, Jamaica and Indonesia; systems were sized with detailed attention to analysis of the solar resource, but not costed. A challenge for hCooking is that cooking on a flame tends to be inherently more energy intensive than eCooking options; i.e. more energy is typically required to prepare a given meal. Hydrogen likely has a similar energy demand to LPG, which is very roughly double that of eCooking – but is still considerably more efficient than charcoal or firewood [2], [7], [14]. In this work, hCooking is considered as a possible rival to eCooking, with a battolyser used to produce hydrogen from solar power.

Clean cooking technologies can face barriers to adoption. Studies carried out in Zambia [15] demonstrate that whilst electricity is the aspirational cooking fuel in the country, charcoal use is also 'deeply embedded'. Poor reliability of the electrical grid has in the past caused many adopters of eCooking to revert to charcoal. Additionally, there are sometimes perceptions that cleaner cooking technologies are more costly than is the case [16], and safety concerns are cited as obstacles to adoption of both LPG and EPCs [15]. On the other hand, fuel stacking of eCook with charcoal is proving to be popular in Zambia, and cooking styles appear compatible with the newer technologies [15].

The environmental impact of cooking technologies has seen various treatments. For instance, in [2], [4] full-scale impact assessment is carried out to make a discrete comparison between the status-quo and the eCooking alternative, whilst in [13], [14] a more limited consideration of operational emissions is included, and in [8] environmental degradation is accounted via a cost factor. In some other sources [5], [9] environmental benefits for eCook are assumed but not quantified. In contrast with previous literature, this work frames emissions curtailment as one objective of a multi-objective optimisation, together with cost. This approach enables understanding the play-off between cost and environmental benefit, and can highlight 'compromise' system designs which achieve less than 100% emissions curtailment, but at cheaper cost.

1.2 Battolysers

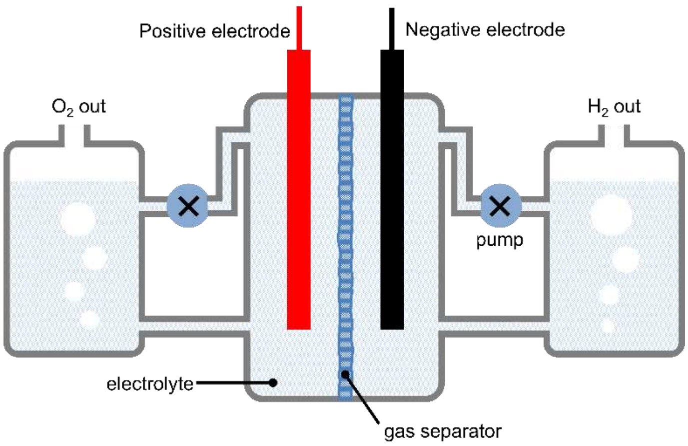

Figure 1. High level schematic of lead-acid battolyser. Adapted from [17].

A battolyser combines the function of both battery and electrolyser in one device. The concept is relatively recent, with the first publication on the subject in 2017 [18]. The battolyser can absorb or produce electricity in the manner of a battery; but when it approaches a fully charged state, it begins to operate as an electrolyser, and hydrogen production commences. Thus, the battolyser can realise both short-term and long-term energy storage with one device. Figure 1 shows a simple schematic of a battolyser. Battolysers require the electrolyte to circulate, since gas bubbles would otherwise impair electrolyte conductivity; consequently they resemble flow batteries [17], [19]. A gas separator ensures that hydrogen and oxygen products do not mix.

The original battolyser concept used a nickel-iron chemistry [18]. Recent work has investigated the potential of a lead-acid battolyser, incentivised by the rising cost of nickel driven by increasing demand for conventional batteries [19]; the lead-acid chemistry could provide for a cheaper battolyser, appropriate for a wider range of customers. Furthermore, since lead-acid batteries are such an established technology due to the application in vehicles, the lead-acid battolyser has a possible advantage in terms of supply chains, manufacturing and even recycling [19]. With the technology still in its infancy, applications for battolysers have received little study as yet. Jenkins et al [17] considered the lead-acid battolyser for the storage of excess energy from offshore windfarms; battolysers were shown to make better economic sense than electrolysers, although there was not a clearcut superiority to batteries in economic terms. Similarly, Wagener [20] considered the nickel-iron battolyser in conjunction with offshore wind, finding that a battolyser CAPEX of < €250 / kW for the year 2050 would make a battolyser system competitive with an electrolyser + flow battery system.

1.3 Contribution of this work

In this work, we assess a battolyser with hCooking as a possible route to cleaner cooking in SSA. The aim of the work is to ascertain whether the battolyser can compete economically with (a) charcoal (representing 'business-as-usual') and (b) eCooking. This will inform decision-making as to whether real-life pilots should be pursued for this application of the battolyser, and what improvements to the battolyser should be prioritised prior to such trials. The environmental benefits of cleaner cooking are also considered, represented by lifetime GHG emissions. By posing the system design as a multi-objective optimisation, we enable the play-off between emissions curtailment and cost to be understood, and can produce a spectrum of designs to achieve different levels of decarbonisation. This work contributes to an extremely small body of research on applications for the battolyser, and is likely the first study to consider an application other than storage of wind power. Likewise, it adds to a rather small body of research considering hCooking in microgrid contexts, and may be the first work to directly compare eCooking and hCooking.

2. Method

2.1 Overview

In this work AnyLogic software [21] is used to simulate a microgrid with renewable energy generation, energy demands for both electrical power and for cooking, and energy storage in the form of either a battery or a battolyser with H_2 storage. Figure 2 shows the various components of the simulation model. OptQuest [22] global optimiser is then used to optimise the simulation parameters – i.e. the sizing of generation and energy storage. Optimisation objectives are the net present cost (NPC) of the microgrid, and its lifetime GHG emissions; thus, optimisation produces a Pareto frontier for the play-off between these objectives. Separate frontiers are produced for systems with eCooking + battery and hCooking + battolyser, enabling the comparison of these alternatives. Individual components of the model will now be presented in more detail.

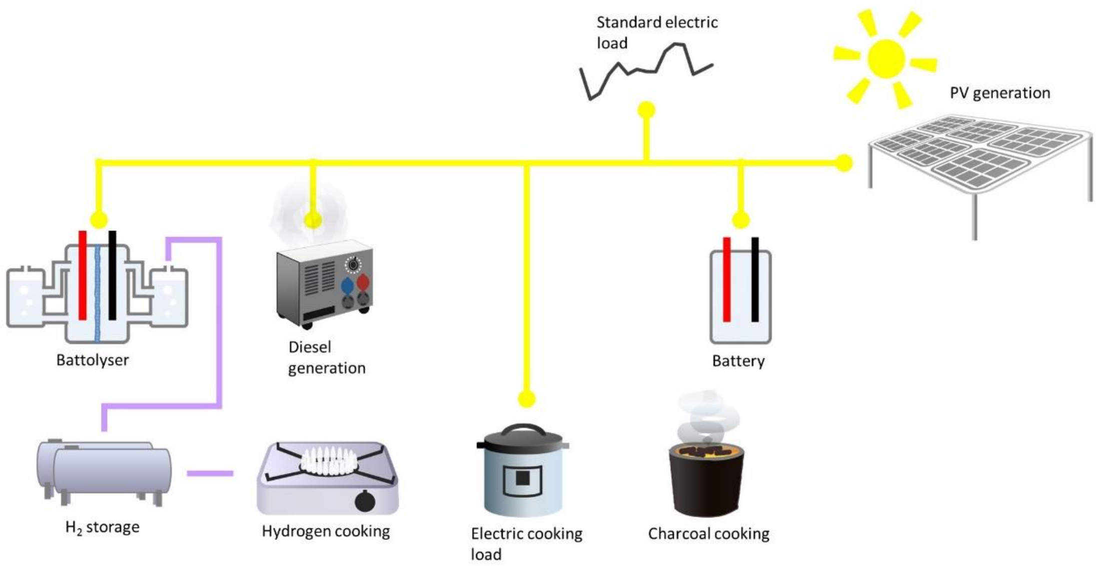

Figure 2. Components of the simulated microgrid with cooking load. N.B. not all components are present in every simulation run.

2.2 Characterisation of microgrid components

2.2.1 Cooking demands

The requirement for heat energy to cook a meal is dependent on the fuel used, as shown in Table 1. It is assumed that the efficiency for hydrogen would be similar to that of LPG, where LPG stoves are known to be around 4 times as efficient as charcoal stoves in energetic terms [2]. Cooking with electricity is yet more efficient. Various electric cooking devices are available, of which the most important are arguably hotplates and EPCs. Scott and Leach report that hotplates are around 5.5 times more efficient than charcoal, and EPCs as much as 15 times as efficient [3]. A realistic scenario with electric cooking uses a mixture of these devices. Here, numbers from Leach et al [2] are adopted, where charcoal has around 13% the efficiency of electric cooking, and LPG / hydrogen 53%. Comparable numbers may be found for instance in Martínez-Gómez et al [23] where LPG is shown to be 57% as efficient as hotplates, and Sweeney et al [24] where gas burners are estimated to be 61% as efficient as hotplates. Sensitivity analysis on the burner efficiency is included in Section 3.4.

Table 1. Demand for cooking energy by fuel, derived from Leach et al [2]. Scaled for 4.2 people per household. Hydrogen fuel is assumed to have the same efficiency as LPG.

Fuel	Cooking demand per house per day (kWh)	Equivalent mass (kg)	Relative efficiency
Charcoal	12.46	1.5 kg	0.13
Hydrogen	3.06	0.092 kg	0.53
Electricity	1.62	-	1.0

Note that the household daily demand for hydrogen would equate to 828g of water on the basis of stoichiometry, or 197g per person per day, a requirement which is relatively small compared to the requirements for drinking, cooking and washing. Regarding the timing of demand for cooking, a demand profile for electric cooking from the Zambia Cooking Diaries [25] is adopted; this was modelled using a combination of survey and meter data. The profile has been slightly smoothed and is shown in Figure 3 with the solar irradiance profile for comparison. Note that the evening meal is prepared after sundown, so solar energy cannot be used directly.

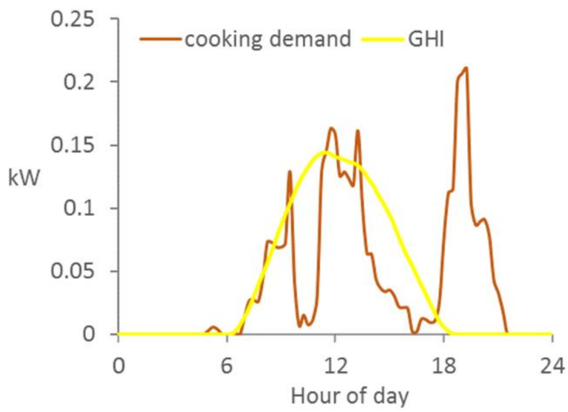

Figure 3. Daily cooking profile from the Zambia cooking diaries [25], with GHI for comparison. In this figure both profiles are normalised to a total of 1 kWh across the whole day.

2.2.2 PV

The PV model uses direct and diffuse irradiance components to calculate the total irradiance on a tilted solar array, similar to [26]. Electrical conversion efficiency is assumed to be up to 15.4%, degrading for module temperature above 25°C, with the temperature coefficient -0.35% / °C. Module temperature is a function of incident radiation, air temperature and wind speed, as specified in the Sandia model [27].

2.2.3 Battery / battolyser

The battery is described by energy capacity E_{batt}^{max} in kWh; power capacity P_{batt}^{max} in kW; round-trip efficiency η_{batt}; state-of-charge range; and parameters for cost and lifetime – see sections 2.5 and 2.6. For simplicity, round-trip losses are assumed to be incurred during battery charging. The state-of-charge range is assumed to be 50 – 100%, which is a common choice to improve cycle life [28], [29]. Power capacity reflects the sizing of installed power electronics, and is also constrained in accordance with the C-rate of the cells, assumed to be 0.5 [30]. Thus the operation of the battery is governed by equations 1-3:

$$\frac{d}{dt}E_{batt}(t) = \eta_{batt} \cdot P_{batt,ch} - P_{batt,dch} \tag{1}$$

$$0.5 \cdot E_{batt}^{max} \leq E_{batt}(t) \leq E_{batt}^{max} \tag{2}$$

$$P_{batt,ch}(t), P_{batt,dch}(t) \leq P_{batt}^{max} \tag{3}$$

The battolyser is modelled identically to the battery, but with the addition of electrolysis efficiency in kWh / kg_{H2} and electrolysis power capacity in kW. It is assumed that hydrogen production with the battolyser commences only when it is fully charged as an electrical energy store, as in [17]. Battery and battolyser are both assumed to be based on a lead-acid chemistry with electrical round trip efficiency 80%. Electrolysis efficiency is assumed to be $62\%_{LHV}$ (53.7 kWh/kg). Costs, degradation and embedded emissions for the battery / battolyser are discussed in sections 2.5 and 2.6.

2.2.4 H_2 storage

The battolyser is assumed to operate at 20 bar pressure, and hydrogen is also stored at this same pressure. Accordingly, a compressor is not needed between the battolyser and the storage. Storage is described by the capacity M_{H2}, in kg_{H2}, as well as the cost and emissions factors given in Section 2.5. 20 bar pressure corresponds to a storage density of ca. 1.69 kg / m^3, or 56 kWh_{LHV} / m^3.

2.2.5 Diesel generation

Diesel generation is characterised by capacity P_{diesel} (kW) and efficiency (kWh / litre).

2.3 Dispatch of microgrid

Dispatch of the simulated microgrid is by a greedy algorithm, which is triggered when any of the following events occur:

- The battolyser / battery becomes fully charged or fully discharged
- The H_2 storage becomes full / empty
- The required power for cooking changes (30 minutely)
- The required standard electric load changes (15 minutely)
- The PV generation output changes (5 minutely)

The greedy algorithm for dispatch of electrical devices is shown in Figure 4. Consumption of hydrogen from the storage is omitted from the flowchart: if hydrogen is available, it is used to fulfil the cooking demand; otherwise charcoal is used.

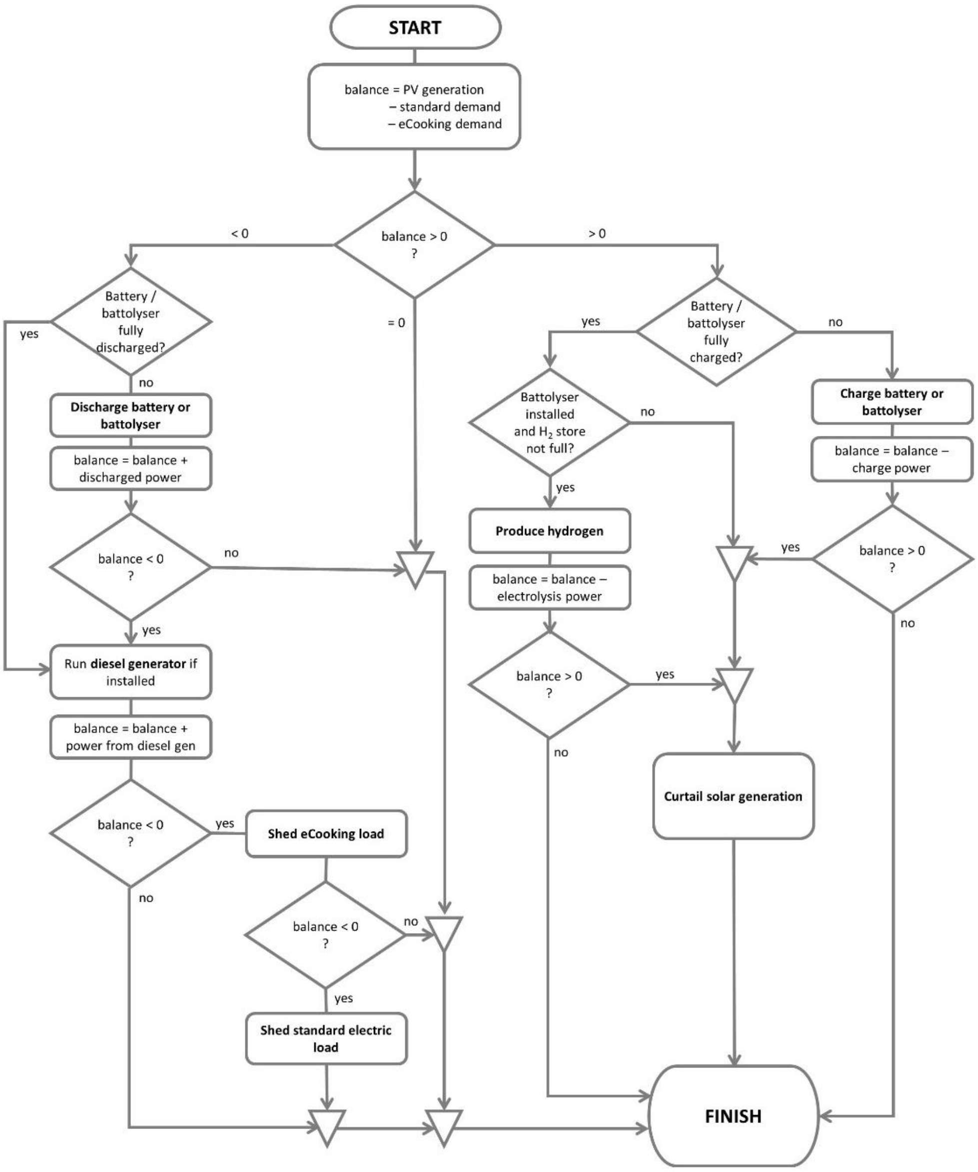

Figure 4. Greedy algorithm for dispatch of the microgrid's electrical devices.

Since the control algorithm is simple and fast to execute, the simulation run-time is kept short enough for use with an optimiser to be practical.

Load shedding by substituting electric or hydrogen cooking with charcoal might not be practical to implement in reality; nonetheless, this aspect ensures that the lack of sufficient clean energy at a particular time is captured by the model and penalised. It is assumed here that production of hydrogen does not commence until the battolyser is fully charged, as in [17].

2.4 Optimisation variables, constraints and requirements

Optimisation employs the OptQuest [22] global optimiser, with each iteration being the simulation of the microgrid for one year. The following subsections detail the variables, constraints and objectives used.

2.4.1 Variables

The multi-objective optimisation involves five binary variables and seven continuous-valued variables, as shown in Table 2. Upper bounds for continuous variables were chosen on the basis of preliminary results, to ensure the search-space is kept small whilst still containing the global optimum.

Table 2. Decision variables for the optimisation.

Symbol	Description	Unit	Type	Domain
b_{btl}	installation of battolyser	-	binary	{0,1}
b_{batt}	installation of battery	-	binary	{0,1}
b_{diesel}	installation of diesel generator	-	binary	{0,1}
b_{elec}	electric cooking	-	binary	{0,1}
b_{H2}	hydrogen cooking	-	binary	{0,1}
E_{btl}^{max}	Energy capacity of battolyser	kWh	continuous	[0, 500]
P_{btl}^{max}	Power capacity of battolyser	kW	continuous	[0, 250]
E_{batt}^{max}	Energy capacity of battery	kWh	continuous	[0, 500
P_{batt}^{max}	Power capacity of battery	kW	continuous	[0, 250]
P_{PV}	PV capacity installed	kW	continuous	[0, 250]
P_{diesel}	Diesel generation capacity installed	kW	continuous	[0, 100]
M_{H2}	Hydrogen storage installed	kg	continuous	[0, 1600]

2.4.2 Constraints

It is assumed that either battery or battolyser is installed, but not both. This is controlled by binary variables b_{btl} and b_{batt}, as given in equations 4 - 8:

$$b_{btl} + b_{batt} \leq 1 \tag{4}$$
$$E_{btl}^{max} \leq 1000 \cdot b_{btl} \tag{5}$$
$$P_{btl}^{max} \leq 1000 \cdot b_{btl} \tag{6}$$
$$E_{batt}^{max} \leq 1000 \cdot b_{batt} \tag{7}$$
$$P_{batt}^{max} \leq 1000 \cdot b_{batt} \tag{8}$$

The choice between eCooking and hCooking is described by Equation 9:

$$b_{elec} + b_{H2} \leq 1 \tag{9}$$

hCooking can only be used if the battolyser is installed:

$$b_{H2} - b_{btl} \leq 0 \tag{10}$$

eCooking is not used if the battolyser is installed (see Section 4 regarding the relaxation of this constraint):

$$b_{elec} + b_{btl} \leq 1 \tag{11}$$

C-rates for the battery / battolyser:

$$P_{btl}^{max} \leq 0.5 \cdot E_{btl}^{max} \tag{12}$$
$$P_{batt}^{max} \leq 0.5 \cdot E_{batt}^{max} \tag{13}$$

H_2 storage is installed only if the battolyser is installed:

$$M_{H2} \leq 1000 \cdot b_{btl} \tag{14}$$

Diesel power rating is constrained by diesel installation variable:

$$P_{diesel} \leq 1000 \cdot b_{diesel} \tag{15}$$

2.4.3 Objectives

The objectives of the multi-objective optimisation are the lifetime GHG emissions and the net present cost (NPC). Lifetime GHG emissions $GHG_{lifetime}$ are the sum of the original embodied emissions GHG_{emb}, and the annual emissions from fuel combustion GHG_n^{fc} and further embodied emissions from equipment replacement GHG_n^{rep}:

$$GHG_{lifetime} = GHG_{emb} + \sum_{n=1}^{20} \left(GHG_n^{fc} + GHG_n^{rep} \right) \tag{16}$$

NPC is given by Equation 17. It consists of capital costs C_{CAPEX}, as well as annual costs for each year *n* of operation: C_n^{OPEX} for equipment OPEX; C_n^{fuel} representing fuel costs; C_n^{rep} for costs of equipment replacement; and C_n^{pen} representing the penalty for any loss-of-load (see below).

$$NPC = C_{CAPEX} + \sum_{n=1}^{20} \frac{\left(C_n^{OPEX} + C_n^{fuel} + C_n^{rep} + C_n^{pen} \right)}{(1+i)^n} \tag{17}$$

where 20 is the assumed lifetime of the project in years, and *i* is the discount rate, assumed as 12%. An inflation rate of 2% is also applied to costs. A penalty of $1 / kWh is applied for any loss of electrical load; this value is considered appropriate being roughly double the marginal cost of running diesel generation, and also an order of magnitude greater than typical electricity prices in Zambia [31]; loss of electrical load for South Africa has been valued at ca. $0.66/kWh for 2018-19 [32]. Loss of load is also required to be below 0.1% of annual electricity demand [33]. Besides NPC, annualised cost will also be discussed, and this represents the uniform annual cash flow that would result in the same overall NPC.

2.5 Cost assumptions

2.5.1 CAPEX

Total CAPEX C_{CAPEX} is calculated from unit costs for the various components of the microgrid, given in Table 3. The unit costs for the battolyser have been calculated as part of the LoCEL-H2 project [34]; the details will be published in due course. 'Low' and 'high' values are relevant to the sensitivity analysis in Section 3.4.

Table 3. CAPEX values

Component	Unit	Cost (USD)	Source
PV	kW	**Baseline**: 1870 **Low**: 1000	[35][36]
Wind turbine	kW	2000	[36][37]
Lead-acid battery - energy component	kWh	274	[28]
Lead-acid battery - power component	kW	195	[28]
Lead-acid battolyser - energy component	kWh	**Baseline**: 357 **Low**: 238	-
Lead-acid battolyser - power component	kW	120	-
Hydrogen storage	kWh	**Baseline**: 20 **Low**: 10 **High**: 50	[10]–[12]
Diesel generator	kW	500	[38]
Diesel tank	-	500	[34]
Hydrogen stove	-	50	[13], [39]
Pressure cooker	-	40	[39]
Hotplate	-	24	[40]
Ceramic charcoal stove	-	4	[39]

2.5.2 OPEX

OPEX is calculated for five microgrid components, as specified in Table 4.

Table 4. OPEX assumptions.

Component	Annual OPEX	Source
PV	\$13 / kW	[41]
Wind turbine	\$50 / kW	[36]
Lead-acid battery / battolyser	\$10 / kW	[17]
Hydrogen storage	1% of CAPEX	[42]
Diesel generator	2% of CAPEX	[36]

2.5.3 Equipment replacement

Equipment replacement is considered for PV, battolyser / battery, diesel tank and diesel generation. Wind generation is also considered as a supplementary option. Replacement of components entails additional costs and also additional GHG emissions. Relevant equipment lifetimes are given in Table 5. It is assumed as a baseline that the battolyser would be capable of 20000 hours of electrolysis, this being towards the low end of the lifetimes achievable by existing electrolyser technology [43].

Table 5. Equipment replacement assumptions

Component	Lifetime	Symbol	Source
Lead-acid battery / battolyser - energy component cycle life	**Baseline**: 1000 cycles **Low**: 500 cycles **High**: 3000 cycles	$L_{btl,cycle}$	[44]
Lead-acid battery / battolyser - energy component calendar life	12 years	$L_{btl,cal}$	[28]
Lead-acid battolyser - energy component electrolysis life	**Baseline**: 20000 hours **High**: 50000 hours	$L_{btl,elec}$	-
Lead-acid battery / battolyser - power component	15 years	-	[45] [38]
Diesel generator	15000 hours	-	[38]
Diesel tank	20 years	-	-
PV	25 years	-	[38], [45]
Wind turbine	25 years	-	[36]

The battolyser is assumed to be degraded by both cycling as an electrical energy store, and by operation as an electrolyser, with both these modes combining to give total annual degradation. Additionally, lifetime does not exceed the assumed calendar life. The lifetime in years before replacement is necessary is thus given by Equation 18:

$$lifetime\ (years) = min\left(L_{btl,cal}, \left(\frac{annual\ cycles}{L_{btl,cycle}} + \frac{annual\ hours\ electrolysis}{L_{btl,elec}}\right)^{-1}\right) \quad (18)$$

The power component of the battolyser cost is separate, and is assumed to be replaced once in the lifetime of the system. System lifetime is conservatively taken as 20 years [46], [47].

2.6 GHG emissions

Embodied emissions are considered for the battery / battolyser, the PV generation and the diesel generation. Embodied emissions are incurred again if equipment is replaced during the project lifetime. For simplicity, the emissions associated with battery / battolyser are assumed to be incurred wholly by the energy component. Due to lack of data, embodied emissions for the battolyser are assumed to be similar to those of the lead-acid battery; whilst the battolyser includes unique components not found in the lead-acid battery (such as electrolyte tanks and circulation pumps) there is some indication in the literature that the contribution of these components may be small [48], [49]. Operational emissions are due to the consumption of diesel or charcoal. Assumptions on emissions are found in Table 6.

Table 6. GHG emissions

Component	Embodied emissions	Source
PV system	**Baseline**: 1500 $kgCO_2/kW$	[50]
	Low: 615 $kgCO_2e/kW$	[51]
	High: 2700 $kgCO_2e/kW$	[52]
Lead-acid battery / battolyser	150 $kgCO_2e/kWh$	[52]
Diesel generator	500 $kgCO_2e/kW$	[52]
Wind turbine	900 $kgCO_2e/kW$	[52]
Fuel	**Emissions**	**Source**
Charcoal	6.65 $kgCO_2e/kg$*	[53]
Diesel	2.7 $kgCO_2e/l$*	[54]

*Including production and combustion

3. Results

3.1 Case study

For the purposes of the solar model, the chosen location is 13.646°S 27.616°E which is Machiya, ca. 90 miles NW of Kabwe, Zambia. Climate data for this location was procured from Solcast [55]. The solar resource for this location is approximately 2000 kWh / m^2 / a, enabling a PV capacity factor approaching 25%. The PV system is almost horizontal, with tilt to the North of just 10°; this orientation was established by including PV azimuth and tilt as variables in early optimisation runs.

Half-hour resolution data for standard electrical load has been obtained from a microgrid project in Tanzania [56]. This project had 47 customers in 2018, rising to 239 by 2021. Here the demand has been rescaled to represent 100 customers. Standard electricity consumption averages only 270 Wh per household per day, and consists mainly of phone chargers and lighting, with some TVs, radios and fridges. If eCooking is added (at 1.62 kWh / household / day) it thus becomes almost 86% of total demand.

For the 100 customers, one day of eCooking demand is 162 kWh; 189 kWh including the standard load. One day of hCooking demand is 306 kWh or 9.2 kg. References to storage durations in terms of days are made with respect to these values.

Charcoal is assumed to cost $0.294 / kg [3], [7], with the energy density being 29.9 MJ / kg. Diesel is assumed to cost $1.18 per litre, with the generator efficiency being 20%, equivalently 2.54 kWh_e per litre.

The results below are worth considering in context of the average income in Zambia, which is in the region $200 - $400 per month [57].

3.2 Overview of results

Figure 5 shows the Pareto frontier for NPC against lifetime emissions, with the breakdown shown for components of NPC. Figure 5 (a) shows systems using hCooking and/or charcoal; Figure 5 (b) shows systems using eCooking and/or charcoal. The Pareto frontiers without breakdown can be seen in Figure 8 (a). The system designs from the extremities of the frontiers, numbered 1 – 4, are of interest for further consideration:

1. The **most carbon intensive** system is found at the right-hand extremity of Figure 5(a). It is the cheapest solution when eCooking is excluded. It uses exclusively charcoal for cooking, with a small PV + diesel + battery system to supply electricity demand. This system has lifetime emissions of 7480 tCO_2e (97.6% from charcoal), and is regarded as the baseline for carbon reduction. This system has NPC $200k and annualised cost $213 / household.

2. The **cheapest eCooking** system is found at the right-hand extremity of Figure 5(b). This system uses eCooking, but only for the first two meals of the day. No battery storage is installed, so the evening meal is still cooked on charcoal. The system has lifetime emissions 3019 tCO_2e, NPC $186k and annualised cost $205 per household.

3. The **lowest carbon battolyser** system is the hCook system found at the left-hand extremity of Figure 5(a). Here, focus is placed on the system achieving ca. 99.5% of the maximum emissions curtailment, since achieving the final 0.5% of curtailment adds 7% to NPC. This system has lifetime emissions 327 tCO_2e, NPC $427k and annualised cost $507 per household.

4. The **lowest carbon battery** system is the eCook system found at the left-hand extremity of Figure 5(b). Again, focus is placed on the system achieving 99.5% of the maximum emissions curtailment: the final 0.5% of curtailment adds 23% to NPC. This system has lifetime emissions 317 tCO_2e, NPC $355k, and annualised cost $422 per household. This system uses exclusively eCooking with no charcoal.

It should be noted that complete curtailment of lifetime emissions is impossible owing to embodied emissions. More details of systems 1 to 4, including the sizing of components, are given in Table 7.

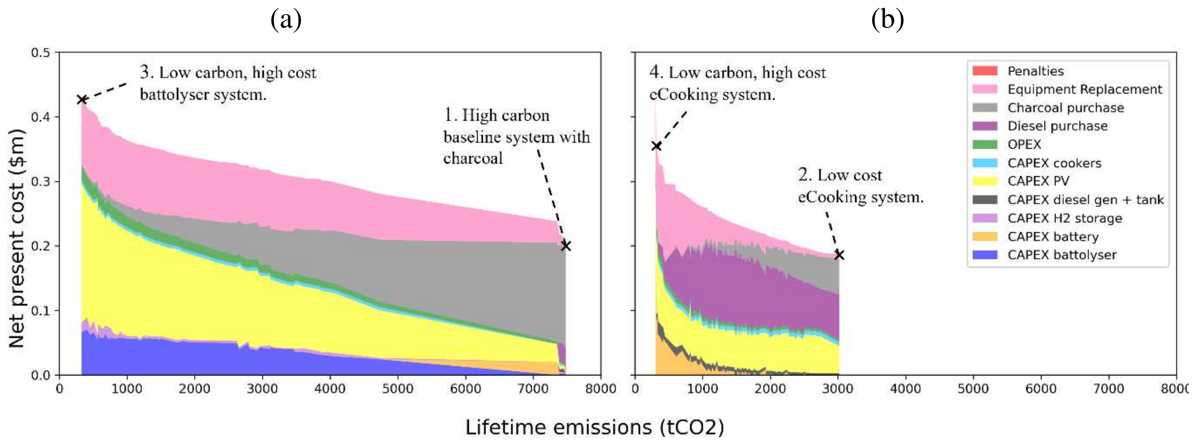

Figure 5. NPC, with breakdown, versus lifetime emissions. (a) Systems with hCooking. (b) Systems with eCooking. The upper edge of each plot gives the Pareto frontier for emissions versus NPC.

Overall, it is clear that the hCook systems in Figure 5(a) are Pareto dominated by the eCook systems in Figure 5(b); in other words, for any desired level of emissions curtailment, eCooking, possibly with a battery, is the cheaper approach. This may be clearer in Figure 8 (a) where the two Pareto frontiers are superimposed. The battolyser systems are closer to being competitive at the more fully decarbonised end of the scale, but are nonetheless still dominated by eCook systems. It is worth noting that a low-carbon hCooking + battolyser system requires around double the amount of PV as for eCooking + battery (see Table 7); this is a result of the inherently higher energy requirement for cooking on a flame.

Consequently, PV CAPEX contributes over 50% of NPC for the low-carbon battolyser system, and only 32% for the battery. The implication is that battolyser + hCook may not be a good technology choice for the application considered here.

It is interesting to note that these results suggest eCooking as financially advantageous as well as environmentally beneficial. Specifically, System 2 cuts three-fifths of emissions compared to System 1, but is also cheaper (see Table 7). This is achieved by only decarbonising the meals during daytime, and continuing to use charcoal for the evening meal, as shown by the average energy profile in Figure 6 (a). Decarbonising the evening meal can be done most cheaply by running eCookers on diesel generation; this can cut around half the remaining emissions. Fuller decarbonisation requires substantial battery storage as in System 4, and is no longer cost-competitive with charcoal.

Table 7. Details of systems 1 – 4.

	(1) Most carbon-intensive system	(2) Cheapest system	(3) Cleanest battolyser system	(4) Cleanest battery system
Cooking	charcoal	eCook + charcoal	hCook + charcoal	eCook
Proportion of cooking on charcoal	100%	36%	0.4%	0%
Battery kW	0.044	-	-	46.3
Battery kWh	0.087	-	-	273.1
Battolyser kW	-	-	80.2	-
Battolyser kWh	-	-	160.4	-
H_2 storage kg	-	-	19.9	-
PV kW	0.80	22.6	117.0	59.9
Curtailed PV	2.65%	9.22%	6.60%	10.7%
Diesel kW	3.36	4.18	-	20.0
Diesel capacity factor	28.4%	43.6%	-	0.25%
NPC $k	200	186	427	355
Lifetime emissions tCO_2e	7480	3019 (-59.6%)	327 (-95.6%)	317 (-95.8%)
Annualised cost $ per household	213	205	507	422

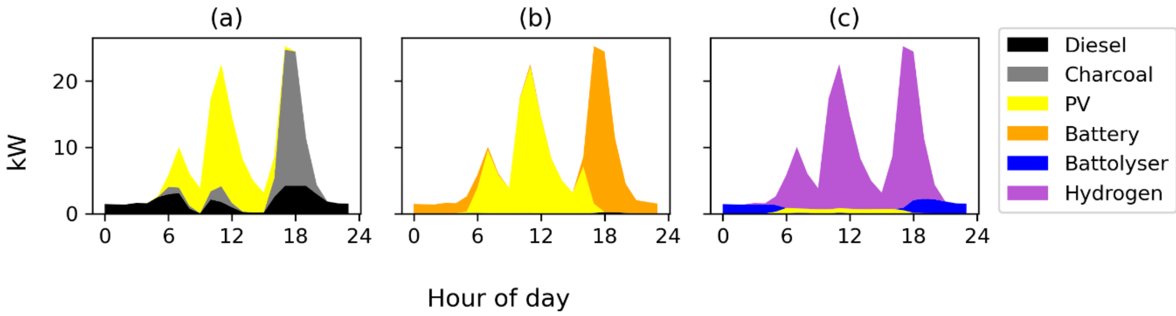

Figure 6. Energy sources providing cooking and standard load, as an average daily profile.
(a) cheapest eCooking system (System 2);
(b) least carbon intensive eCooking system (System 4);
(c) System 3 - least carbon-intensive hCooking system (System 3).
Cooking supplied by charcoal or hydrogen is plotted according to the equivalent electrical demand, resulting in an identical aggregate profile across (a) (b) and (c). Energy for battery charging is not shown, and nor is curtailed generation. Note that in (c), direct use of solar power for cooking is impossible; all PV energy must be converted to hydrogen prior to use for cooking.

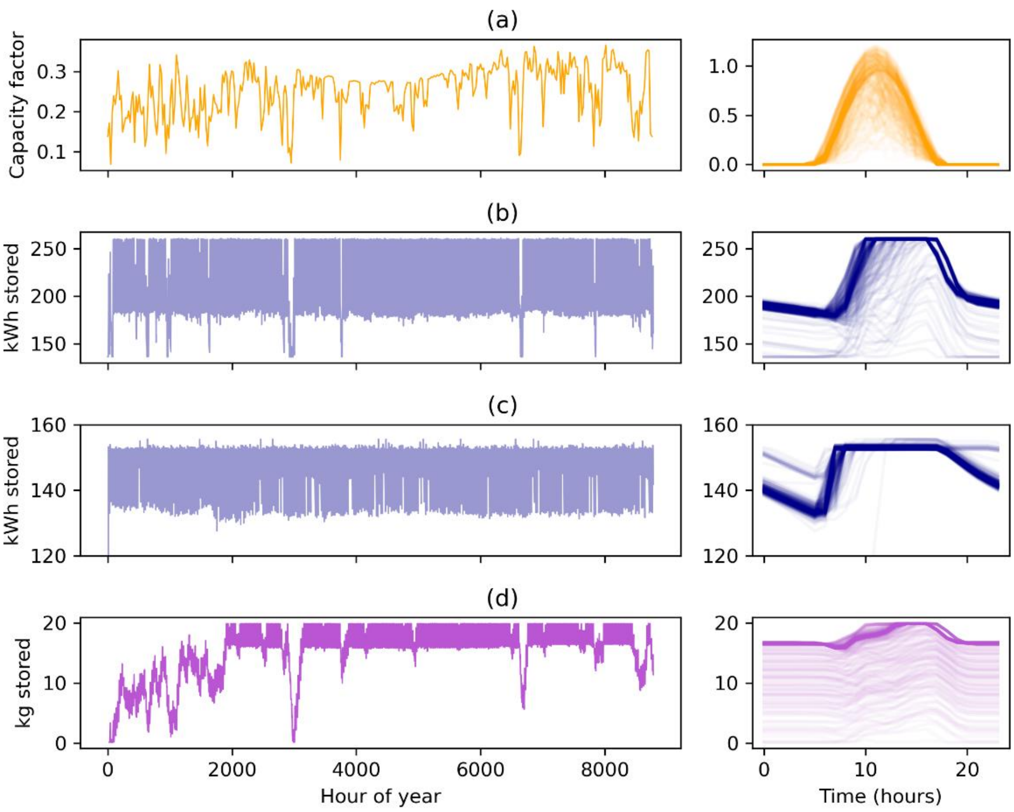

Figure 7. Cycling of energy storages, with solar resource for comparison. Columns 1 and 2 respectively show the annual and the diurnal profiles. (a) Solar capacity factor (daily average in column 1). (b): Battery state-of-charge for System 4 (low carbon battery system). (c) and (d): Respectively, battolyser and H_2 tank state-of-charge for System 3 (low carbon battolyser system).

3.3 Storage size and cycling

Figure 7 shows the cycling of energy storage for the highly decarbonised systems, with the solar resource for context. 7 (b) shows the cycling of the battery in System 4; 7 (c) and (d) show the cycling of respectively the battolyser and the hydrogen store in System 3. The solar resource is relatively reliable; it is most intermittent in the rainy season (approximately November to April) which is reflected in the increased cycling of storage in this part of the year. The most pronounced discharge of storage occurs on 4th May, after three consecutive days of low irradiance, unusual in Zambia. The high reliability of the solar resource is reflected in the designed storage durations: System 4 has battery storage of only 0.84 days, while System 3 has H_2 storage for 2.2 days of cooking demand. As an electrical energy store, the battolyser undergoes rather shallow cycles after its initial charge, remaining in the state-of-charge range 80 – 100%. This reflects the low demand for electricity when excluding eCooking; the shallow cycling should be beneficial for minimising degradation. Total CAPEX on energy storage is similar in each case: $80.1k (27%) for the battolyser and H_2 storage in System 3; $83.9k (40.4%) for battery storage in System 4. Whilst the total energy storage CAPEX is less per kWh for the hydrogen system, the inherent inefficiencies in the hydrogen system tend to cancel out this advantage. The eCook system also has an advantage in that only part of the day's demand need be stored (the part not coincident with the solar resource). Given the relatively short storage durations, it is possible that a more intermittent energy source would provide better justification for the hCooking system.

3.4 Sensitivity analysis

As above, hCook systems with the battolyser are generally Pareto dominated by eCook systems, with respect to the optimisation objectives of cost and lifetime emissions; this can be seen in Figure 8 (a). This conclusion was subjected to sensitivity analysis on battolyser and battery lifetime; battolyser, H_2 store and PV costs; and hob efficiency. The specific values used are given as **low** or **high** limits in Section 2.5. Additionally, results were repeated with the use of diesel disallowed; note that all Pareto optimal solutions with eCook made some use of diesel in the original results. The Pareto frontiers under sensitivity analysis are presented in Figure 8 (b) – (g).

- A battolyser with significant improvements to lifetime (e.g. 3000 cycles or 50000 hours of electrolysis) could be competitive with the eCook system – see Figure 8 (b). However, this is only true for systems with the very highest level of decarbonisation. Four replacements of the battolyser energy components would be required for System 3 under baseline assumptions; increased cycle life would decrease this to three; increased electrolysis life would decrease it to two.
- Figure 8 (c) shows the results of varying battery lifetime for the eCook systems. The impact is greater than for the battolyser, and a cycle life of 3000 could bring the annualised cost of System 4 down to $269 per household, which could be an acceptable cost when compared with the cost of charcoal. Cycle life of 3000 would enable only one battery replacement during the project lifetime.
- Variation in the cost of H_2 storage has virtually no impact on the Pareto frontier, which is unsurprising given the negligible contribution of H_2 storage to NPC (see Figure 5(a)). Longer storage durations would be needed for this to be an important factor. A reduction by one third in the cost per kWh of the battolyser, which is considered realistic for the future, would have more impact, but the battolyser systems continue to be dominated by the eCook systems in this case.
- Battolyser systems require a large capacity of PV, as already stated. System NPC is very sensitive to PV cost and a reduction would close the gap with eCooking, although eCooking would remain optimal. See Figure 8 (e).

- Removing the option to use diesel as backup significantly increases the cost of eCook systems at moderate levels of decarbonisation, as shown in Figure 8 (f). However, the eCook systems largely remain preferable to the hCook systems.

Figure 8 (g) shows the potential impact of varying hydrogen burner efficiency (see also Section 2.2.1). It is clear that the inferior efficiency for hCook in the base case is a main driving factor behind the dominance of the eCook systems. If the hydrogen hob could match the efficiency of eCooking devices, or even achieve 75% of the efficiency, hCooking with the battolyser would be the cheaper way to achieve deep cuts to lifetime emissions. It is plausible that progress could be made towards closing the efficiency gap, as described for instance in Zhang et al [58].

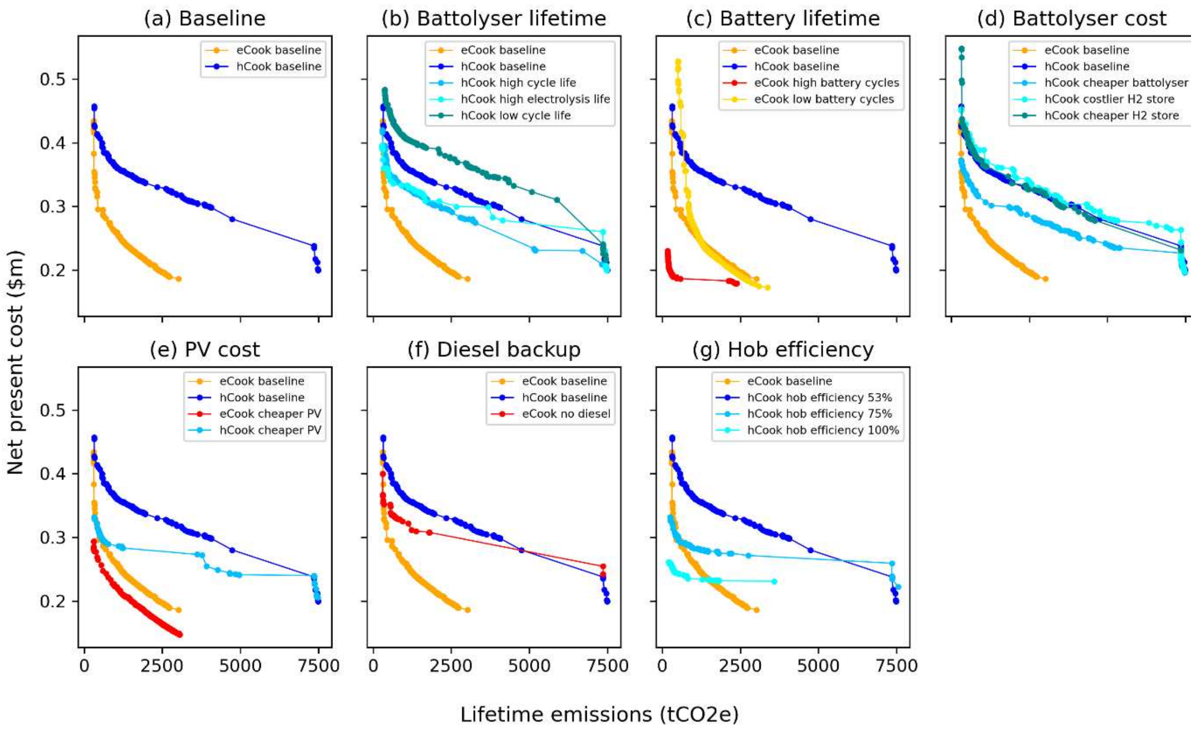

Figure 8 Pareto frontiers under sensitivity analysis. Generally, the eCooking systems continue to dominate the hCooking systems, with rare exceptions. Regarding (g), recall that 'efficiency' is relative to the eCooking consumption.

3.5 Alternative scenarios

Results have demonstrated that under most scenarios, the battolyser + hCook system does not compete with battery + eCook. This is ascribed mainly to the inherently higher efficiency of eCooking, which importantly allows for much less PV generation to be installed.

The main advantage of hydrogen for energy storage is the low per kWh cost, which allows for bulk, long duration storage. The reliable nature of the solar resource in the case study (the longest dip in generation was only three days) means that long duration storage isn't required. Accordingly, two additional experiments were conducted: (1) swapping the PV generation for wind power, which might be expected to exhibit longer term variations, and (2) moving the PV case study location to Rwanda, which experiences a much less reliable solar resource. Wind speed data for the Zambia case study was rescaled to enforce an annual wind capacity factor of 25%, using the power curve for a 150 kW turbine [59]; this capacity factor is known to be achievable in some regions of SSA [60]. Irradiance data for Rwanda was obtained from Solcast as before, with the total GHI being 1647 kWh/m^2/a.

The additional results are shown in Figure 9 (wind power, Zambia) and Figure 10 (PV power, Rwanda). Battolyser + hCook systems are Pareto-dominated by battery + eCook systems as before. Powering the microgrid with wind is significantly more expensive overall, which is likely because the solar resource actually synchronises better with the cooking demand than wind (cosine similarity 0.50 for wind, 0.62 for PV). Similarly, moving the case study to Rwanda increases overall cost, owing to the inferior solar resource, but battery + eCook remains preferable to battolyser + hCook.

(a) (b)

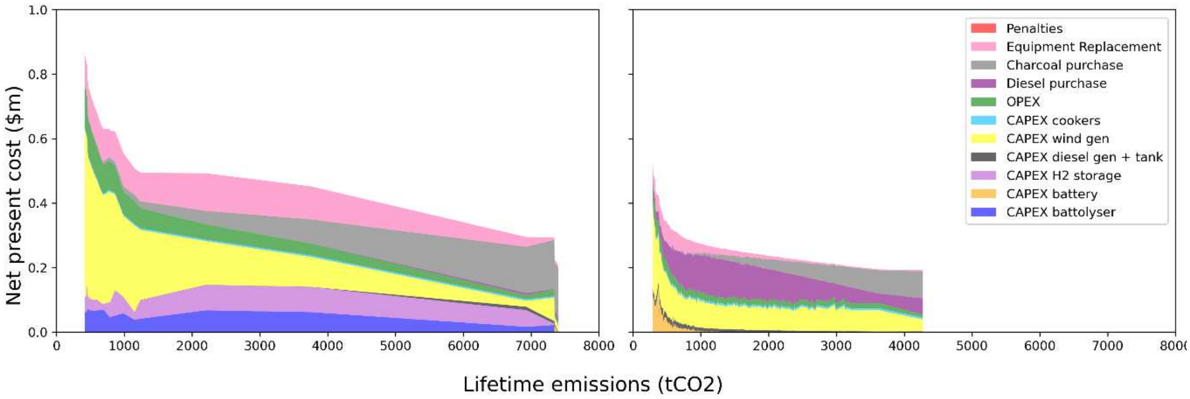

Figure 9. NPC, with breakdown, versus lifetime emissions, with **wind generation replacing PV**. (a) Systems with hCooking. (b) Systems with eCooking. The upper edge of each plot gives the Pareto frontier for emissions versus NPC. Cost and emissions metrics for wind are given in Section 2.

(a) (b)

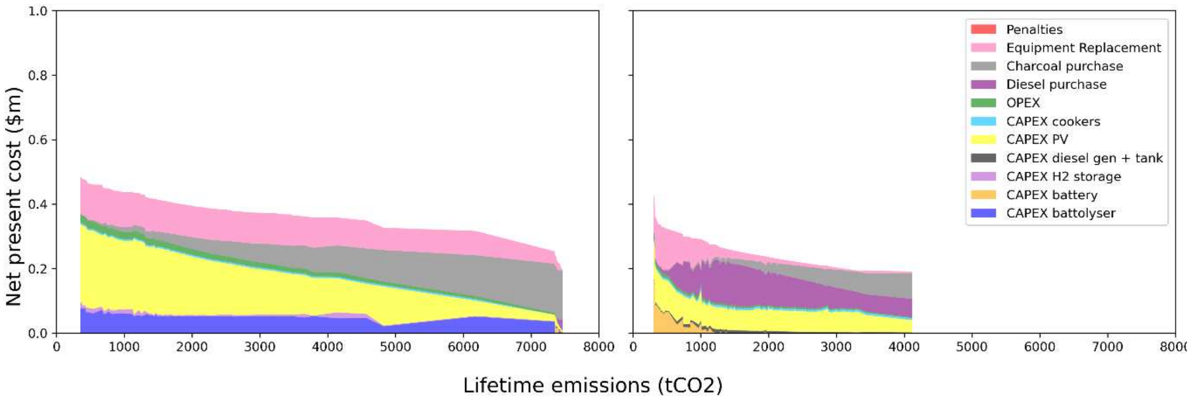

Figure 10. NPC, with breakdown, versus lifetime emissions, for Rwanda, which has a more variable solar resource. (a) Systems with hCooking. (b) Systems with eCooking. The upper edge of each plot gives the Pareto frontier for emissions versus NPC.

4. Discussion

With results showing the hCooking + battolyser system to be Pareto dominated by eCooking systems in most scenarios, it is of interest to explore where any potential of the battolyser has not been fully realised. For instance, Figure 7 (c) shows that the potential of the battolyser as an electrical energy store as well as an electrolyser is not necessarily well used; cycling of the battolyser was only in the range 80 – 100%. With the aggregate electricity demand of 100 households being only 27 kWh / day, the electrical storage has limited value if eCooking is not used. Higher electrical demand could perhaps improve the case for the battolyser. One possible approach would be to use a mix of eCook and hCook, so that electrical discharge of the battolyser can supply some eCook demand. Original results did not allow this, imposing a binary choice between hCook and eCook, and enforcing the use of hCook with the battolyser. Accordingly, the constraint from Equation 11 was relaxed, and a proportional split between hCook and eCook was permitted. The somewhat unexpected result was that the optimiser assigned 100% of cooking to eCooking, and the battolyser was used purely as an electrical energy store, with no use for any hydrogen produced. The Pareto frontier was similar to the baseline curve for eCook, although slightly less favourable owing to the unnecessary additional cost of battolyser versus battery. This rather emphasises the difficulty in finding a good case for hCooking.

It is interesting to consider a different possible approach, where stored hydrogen is used in a fuel cell to generate power for eCooking. In fact this comparison was made by Schöne et al [13]. Such an approach avoids the efficiency penalty of hCook versus eCook (estimated at 53% in this work). However, a similar inefficiency would instead be introduced by the fuel cell, which would likely offer efficiency of roughly $60\%_{LHV}$. With the capital costs associated with the fuel cell, it is unsurprising that Schöne et al found direct combustion of the hydrogen to be preferable.

Network cost (for either electricity or hydrogen) has not been considered here. This is partly justified by the long life of this infrastructure relative to the energy components, probably at least 40 years [45]. Further, the cost of installing a hydrogen network in this type of context is rather uncertain. It is likely that consideration of networks would only emphasize the superiority of the eCooking option – especially as a high capacity electrical network could enable many new appliances to be introduced, not only eCookers; a hydrogen network, by contrast, would be single purpose. It is possible that hydrogen dispensing to households could be achieved without a pipe network; for instance [14] envisages hydrogen delivered in metal hydride storage. Safety, and also the perception of safety, will be a key concern for any hydrogen project, given that even EPCs and LPG have caused concern for users in this respect [15].

There is a possibility that a battolyser with very good durability (e.g. 50000 hours of electrolysis or 3000 cycles) could be close to competitive with an eCooking system. However, even if this durability could be achieved, there are more factors to consider. Firstly, as mentioned, costs of dispensing the hydrogen to users have not been considered in this introductory study. Secondly, hydrogen is highly volatile and difficult to handle safely. Thirdly, the battery system is likely more versatile as it will enable adoption of other appliances, not limited to cooking.

Although this study's results suggest that it is challenging to find an application for the battolyser in decarbonisation of cooking, from a wider perspective the results are encouraging. In the case study, 60% of lifetime GHG emissions could be eliminated by a switch to eCooking, whilst actually saving money relative to the base case with charcoal. This backs up previous results in the literature, such as Antonanzas-Torres et al [4] and Lombardi et al [5] which suggested that eCook cost-competitivity was a possibility. Here, results show that 69% emissions curtailment could be achieved before the base case cost is exceeded. The difficulty is in decarbonising the evening meal; significant use of battery storage does lead to a higher cost than the base case. The annualised cost of a highly decarbonised system is \$422 per household, against \$213 for continuing charcoal use; recall that the average income in Zambia is in the region \$200 - \$400 per month [57].

4.1 Limitations and future work

In this work, attempt has not been made to quantify benefits of a switch away from charcoal, beyond the GHG abatement and possible financial savings. A future study could broaden the analysis to encompass other important factors, which might include the health benefits of cleaner cooking that arise from reduced air pollution, and the knock-on economic benefits of this; as well as the creation of jobs in the renewable energy sector. Additional economic benefits might result from eCooking in particular, since a microgrid able to support it should also be able to support the adoption of other appliances.

The three cooking fuels considered in this work were charcoal, hydrogen and electricity. Leach et al [2] demonstrated the value of stacking LPG with alternative fuels, and perhaps battolyser with LPG backup could be considered in the future.

Lead-acid chemistry was assumed for the conventional battery in this work. Whilst lead-acid batteries are common for microgrids in the region, consideration of Li-ion chemistry might be worthwhile for future studies.

The degradation of the battolyser has not been modelled in detail in this work. The very shallow cycling in this study could be beneficial to cycle life, and this could be modelled more explicitly in future analyses. Also it is assumed here that production of hydrogen does not commence until the battolyser is fully charged, as in [17]. This is a simplification, and a more accurate model of hydrogen production might impact the case for the battolyser. It would also be desirable to conduct a full LCA for the battolyser, for a more accurate understanding of its environmental impacts.

5. Conclusions

This study considered a battolyser for the production of hydrogen for cleaner cooking ("hCooking") in sub-Saharan Africa. The battolyser was compared to electric cooking options ("eCooking") and to the status quo using charcoal. Multi-objective optimisation was employed to assess the playoff between lifetime greenhouse gas emissions and cost. The baseline case with charcoal was shown to result in lifetime emissions of 74.8 tCO_2e per household over 20 years, and annualised cost \$213 per household. Results show that a battolyser system could eliminate 95.6% of lifetime CO_2 emissions when compared with a baseline using charcoal, at an annualised cost of \$507 per household. However, eCooking systems appear superior to the battolyser, with the cleanest battery + eCook system achieving 95.8% emissions reduction at annualised cost \$422 / household. eCooking systems are generally Pareto dominant over hCooking systems, including under a realistic range of sensitivity scenarios. The preference for eCooking arises mainly from its inherently superior efficiency, versus cooking over a flame. If the efficiency of hydrogen burners can be increased it will greatly benefit the case for the battolyser. Increasing the lifetime of the battolyser, thus reducing the number of required cell replacements, should be another priority to improve competitivity; the battolyser will also benefit from cheaper PV systems.

Encouragingly, eCooking with PV and diesel plus continuing use of some charcoal appears to be the cheapest possible way to cook. Such a system will curtail 60% of GHG emissions over that timeframe, whilst actually reducing annualised cost to $205 / household. Reducing the use of charcoal further and adding battery storage can all but eliminate GHG emissions but is more costly. However, supposing a higher battery cycle life of 3000 could be attained, 97.5% emissions reductions could be achieved for annualised cost $269 per household, close to the baseline costs. It is important to note that cleaner cooking can lead to multiple benefits beyond GHG curtailment, notably improved air quality.

These results suggest that the priorities for both government policy and academic research should reflect that eCooking is the front-runner for cleaner cooking in sub-Saharan Africa. Nonetheless, hCooking may find its niche, and research should continue to address the difficulties with cost and efficiency.

Acknowledgements

We would like to thank Hannah Mottram and the Mpale village microgrid for providing electrical load data used in this study.

The authors from Loughborough would like to thank the EU for co-funding parts of this work under project LoCEL-H2.

References

[1] C. Philibert, “Power to the Cooks! New Clean Cooking Opportunities for Sustainable Development in Sub-Saharan Africa,” 2022. [Online]. Available: https://www.ifri.org/sites/default/files/atoms/files/philibert_power_to_the_cooks_2022.pdf.

[2] M. Leach *et al.*, “Modelling the costs and benefits of moving to Modern Energy Cooking Services-methods & application to three case studies Working Paper 29 th April 2021,” 2021. [Online]. Available: www.mecs.org.uk.

[3] N. Scott and M. Leach, “Comparing energy consumption and costs – from cooking across the MECS programme,” 2022. [Online]. Available: https://mecs.org.uk/wp-content/uploads/2022/04/Comparing-energy-consumption-and-costs-–-from-cooking-across-the-MECS-programme.pdf.

[4] F. Antonanzas-Torres, R. Urraca, C. A. C. Guerrero, and J. Blanco-Fernandez, “Solar E-Cooking with Low-Power Solar Home Systems for Sub-Saharan Africa,” *Sustainability*, vol. 13, no. 21, p. 12241, Nov. 2021, doi: 10.3390/su132112241.

[5] F. Lombardi, F. Riva, M. Sacchi, and E. Colombo, “Enabling combined access to electricity and clean cooking with PV-microgrids: new evidences from a high-resolution model of cooking loads,” *Energy Sustain. Dev.*, vol. 49, pp. 78–88, Apr. 2019, doi: 10.1016/j.esd.2019.01.005.

[6] MECS, “MECS Modern Energy Cooking Services,” *mecs.org.uk*, 2023. https://mecs.org.uk/.

[7] ESMAP, “Cooking Electricity With a Cost Perspective,” 2020. [Online]. Available: https://documents1.worldbank.org/curated/en/920661600750772102/pdf/Cooking-with-Electricity-A-Cost-Perspective.pdf.

[8] R. Van Buskirk, L. Kachione, G. Robert, R. Kanyerere, C. Gilbert, and J. Majoni, “How to Make Off-Grid Solar Electric Cooking Cheaper Than Wood-Based Cooking,” *Energies*, vol. 14, no. 14, p. 4293, Jul. 2021, doi: 10.3390/en14144293.

[9] S. Batchelor, E. Brown, J. Leary, N. Scott, A. Alsop, and M. Leach, “Solar electric cooking in Africa: Where will the transition happen first?,” *Energy Res. Soc. Sci.*, vol. 40, pp. 257–272, Jun. 2018, doi: 10.1016/j.erss.2018.01.019.

[10] E. Rivard, M. Trudeau, and K. Zaghib, “Hydrogen storage for mobility: A review,” *Materials (Basel).*, vol. 12, no. 12, 2019, doi: 10.3390/ma12121973.

[11] D. Steward *et al.*, “Lifecycle Cost Analysis of Hydrogen Versus Other Technologies for Electrical Energy Storage Lifecycle Cost Analysis of Hydrogen Versus Other Technologies for Electrical Energy Storage,” no. November, 2009.

[12] B. D. James, C. Houchins, J. M. Huya-Kouadio, and D. A. Desantis, “Final Report: Hydrogen Storage System Cost Analysis,” no. September, pp. 1–54, 2016.

[13] N. Schöne, R. Dumitrescu, and B. Heinz, “Techno-Economic Evaluation of Hydrogen-Based Cooking Solutions in Remote African Communities—The Case of Kenya,” *Energies*, vol. 16, no. 7, p. 3242, Apr. 2023, doi: 10.3390/en16073242.

[14] E. Topriska, M. Kolokotroni, Z. Dehouche, D. T. Novieto, and E. A. Wilson, “The potential to generate solar hydrogen for cooking applications: Case studies of Ghana, Jamaica and Indonesia,” *Renew. Energy*, vol. 95, pp. 495–509, Sep. 2016, doi: 10.1016/j.renene.2016.04.060.

[15] J. Leary, N. Scott, N. Serenje, F. Mwila, and S. Batchelor, “Opportunities & Challenges for eCook Zambia,” 2019. [Online]. Available: https://mecs.org.uk/wp-content/uploads/2020/12/eCook-Zambia-Country-Working-Paper-2-11-19-

COMPRESSED.pdf.

[16] Malawi Ministry of Energy, “Malawi eCooking roadmap,” 2024. [Online]. Available: https://mecs.org.uk/wp-content/uploads/2024/04/Malawi-eCooking-Roadmap-Digital-Version-V9.pdf.

[17] B. Jenkins *et al.*, “Techno-Economic Analysis of Low Carbon Hydrogen Production from Offshore Wind Using Battolyser Technology,” *Energies*, vol. 15, no. 16, p. 5796, Aug. 2022, doi: 10.3390/en15165796.

[18] F. M. Mulder, B. M. H. Weninger, J. Middelkoop, F. G. B. Ooms, and H. Schreuders, “Efficient electricity storage with a battolyser, an integrated Ni–Fe battery and electrolyser,” *Energy Environ. Sci.*, vol. 10, no. 3, pp. 756–764, 2017, doi: 10.1039/C6EE02923J.

[19] M. Brenton, J. Barton, D. Strickland, J. Wilson, and U. Wijayantha-Kahagala, “Lead-acid battolyser concept,” in *11th International Conference on Power Electronics, Machines and Drives (PEMD 2022)*, 2022, pp. 64–70, doi: 10.1049/icp.2022.1018.

[20] H. Wagener, A. J. M. van Wijk, F. M. Mulder, and M. B. Zaaijer, “A future techno-economic evaluation of an offshore wind hydrogen system with battolyser technology on the Dogger Bank,” *Delft University of Technology*, 2023. https://repository.tudelft.nl/islandora/object/uuid%3Aa4ef75d8-19d4-4ae8-9397-75f785911158.

[21] The AnyLogic Company, “AnyLogic,” 2019. https://www.anylogic.com/.

[22] OptTek Systems Inc., “OptQuest,” 2019. .

[23] J. Martínez-Gómez, D. Ibarra, S. Villacis, P. Cuji, and P. R. Cruz, “Analysis of LPG, electric and induction cookers during cooking typical Ecuadorian dishes into the national efficient cooking program,” *Food Policy*, vol. 59, pp. 88–102, Feb. 2016, doi: 10.1016/j.foodpol.2015.12.010.

[24] M. Sweeney, J. Dols, B. Fortenbery, and F. Sharp, “Induction Cooking Technology Design and Assessment,” in *ACEEE Summer Study on Energy Efficiency in Buildings*, 2013.

[25] J. Leary, N. Scott, N. Serenje, F. Mwila, and S. Batchelor, “eCook Zambia Cooking Diaries – October 2019 Working Paper,” 2019. [Online]. Available: https://mecs.org.uk/wp-content/uploads/2020/12/eCook-Zambia-Cooking-Diaries-Report-JL-13-10-19-COMPRESSED.pdf.

[26] T. D. Hutty, S. Dong, and S. Brown, “Suitability of energy storage with reversible solid oxide cells for microgrid applications,” *Energy Convers. Manag.*, vol. 226, p. 113499, Dec. 2020, doi: 10.1016/j.enconman.2020.113499.

[27] Sandia National Laboratories, “Sandia Module Temperature Model,” *sandia.gov*. https://pvpmc.sandia.gov/modeling-steps/2-dc-module-iv/module-temperature/sandia-module-temperature-model/.

[28] K. Mongird, V. Viswanathan, J. Alam, C. Vartanian, V. Sprenkle, and R. Baxter, “2020 Grid Energy Storage Technology Cost and Performance Assessment,” 2020. [Online]. Available: https://www.pnnl.gov/sites/default/files/media/file/PSH_Methodology_0.pdf.

[29] Greentech Renewables, “How does Depth of Discharge factor into Grid Connected battery systems?,” *greentechrenewables.com*, 2024. https://www.greentechrenewables.com/article/how-does-depth-discharge-factor-grid-connected-battery-systems.

[30] Battery University, “BU-403: Charging Lead Acid,” *batteryuniversity.com*, 2023. https://batteryuniversity.com/article/bu-403-charging-lead-acid.

[31] Climatescope, “Zambia,” 2024. https://www.global-climatescope.org/markets/zm/.

[32] K. Walsh, R. Theron, A. Seedat, and C. Reeders, “Estimating the economic cost of load shedding in South Africa,” 2020. [Online]. Available: https://www.nersa.org.za/wp-content/uploads/2021/09/Appendix-C_Estimating-the-Economic-Cost-of-Load-Shedding-in-South-Africa-Report.pdf.

[33] F. C. Robert, G. S. Sisodia, and S. Gopalan, “Sustainable trade-off between reliability and electricity prices for geographically isolated communities,” *Energy Reports*, vol. 5, pp. 1399–1407, Nov. 2019, doi: 10.1016/j.egyr.2019.09.064.

[34] LoCEL-H2, “LoCEL-H2,” *locelh2.org*, 2023. https://locelh2.org/.

[35] IRENA, “Solar PV in Africa - costs and markets,” 2016. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Solar_PV_Costs_Africa_2016.pdf.

[36] J. M. Hansen and G. A. Xydis, “Rural electrification in Kenya: a useful case for remote areas in sub-Saharan Africa,” *Energy Effic.*, vol. 13, no. 2, pp. 257–272, Feb. 2020, doi: 10.1007/s12053-018-9756-z.

[37] A. Okunlola, O. Evbuomwan, H. Zaheer, and J. Winklmaier, “Assessment of Decentralized Hybrid Mini-grids in Sub-Saharan Africa: Market Analysis, Least-Cost Modelling, and Job Creation Analysis,” 2018, pp. 21–34.

[38] S. Keddar, S. Strachan, B. Soltowski, and S. Galloway, “An Overview of the Technical Challenges Facing the Deployment of Electric Cooking on Hybrid PV/Diesel Mini-Grid in Rural Tanzania—A Case Study Simulation,” *Energies*, vol. 14, no. 13, p. 3761, Jun. 2021, doi: 10.3390/en14133761.

[39] J. Leary and B. Onjala, “Is Electricity Really too Expensive for Cooking?,” *mecs.org.uk*, 2022. https://mecs.org.uk/blog/is-electricity-really-too-expensive-for-cooking/.

[40] J. Leary and J. F. Todd, *The Kenya eCookbook*. 2019.

[41] R. H. Wiser, M. Bolinger, and J. Seel, “Benchmarking Utility-Scale PV Operational Expenses and Project Lifetimes: Results from a Survey of U.S. Solar Industry Professionals,” *Electricity Markets and Policy*, 2020. https://emp.lbl.gov/publications/benchmarking-utility-scale-pv.

[42] J. Gorre, F. Ruoss, H. Karjunen, J. Schaffert, and T. Tynjälä, “Cost benefits of optimizing hydrogen storage and methanation capacities for Power-to-Gas plants in dynamic operation,” *Appl. Energy*, vol. 257, no. August 2019, 2020, doi: 10.1016/j.apenergy.2019.113967.

[43] I. Dincer and C. Acar, “Review and evaluation of hydrogen production methods for better sustainability,” *Int. J. Hydrogen Energy*, vol. 40, no. 34, pp. 11094–11111, 2014, doi: 10.1016/j.ijhydene.2014.12.035.

[44] K. Mongird *et al.*, “Energy Storage Technology and Cost Characterization Report | Department of Energy,” no. July, 2019.

[45] A. González-García, P. Ciller, S. Lee, R. Palacios, F. de Cuadra García, and J. I. Pérez-Arriaga, “A Rising Role for Decentralized Solar Minigrids in Integrated Rural Electrification Planning? Large-Scale, Least-Cost, and Customer-Wise Design of Grid and Off-Grid Supply Systems in Uganda,” *Energies*, vol. 15, no. 13, p. 4517, Jun. 2022, doi: 10.3390/en15134517.

[46] T. Reber, S. Booth, D. Cutler, X. Li, and J. Salasovich, “TARIFF CONSIDERATIONS FOR MICRO-GRIDS IN SUB-SAHARAN AFRICA,” 2018. [Online]. Available: https://www.nrel.gov/docs/fy18osti/69044.pdf.

[47] GET.invest, “Zambia: Solar PV and Hydro Mini-Grids,” Brussels, 2019. [Online]. Available: https://www.get-invest.eu/wp-content/uploads/2020/10/GETinvest-Market-

Insights_ZMB_Mini-grid_-CS-Solar_2019-1.pdf.

[48] S. Weber, J. F. Peters, M. Baumann, and M. Weil, “Life Cycle Assessment of a Vanadium Redox Flow Battery,” *Environ. Sci. Technol.*, vol. 52, no. 18, pp. 10864–10873, Sep. 2018, doi: 10.1021/acs.est.8b02073.

[49] E. Shittu *et al.*, “Life cycle assessment of soluble lead redox flow battery,” *J. Clean. Prod.*, vol. 337, p. 130503, Feb. 2022, doi: 10.1016/j.jclepro.2022.130503.

[50] The Renewable Energy Hub UK, “SOLAR PHOTOVOLTAICS – CRADLE-TO-GRAVE ANALYSIS AND ENVIRONMENTAL COST.,” *renewableenergyhub.co.uk*, 2018. https://renewableenergyhub.co.uk/main/solar-panels/solar-panels-carbon-analysis/.

[51] A. Louwen, W. G. J. H. M. van Sark, A. P. C. Faaij, and R. E. I. Schropp, “Re-assessment of net energy production and greenhouse gas emissions avoidance after 40 years of photovoltaics development,” *Nat. Commun.*, vol. 7, no. 1, p. 13728, Dec. 2016, doi: 10.1038/ncomms13728.

[52] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. Weidema, “The ecoinvent database version 3 (part I): overview and methodology,” *Int. J. Life Cycle Assess.*, vol. 21, no. 9, pp. 1218–1230, Sep. 2016, doi: 10.1007/s11367-016-1087-8.

[53] A. A. Sitoe, “Charcoal, carbon emissions, and international conventions/protocols,” Maputo, 2012. [Online]. Available: https://energypedia.info/images/4/4a/EN-Charcoal%2C_carbon_emissions_and_international_onventions%3Bprotocols-Almeida_A._Sitoe.pdf.

[54] M. A. Elsayed, R. Matthews, and N. Mortimer, *Carbon and Energy Balances for a Range of Biofuels Options*. 2003.

[55] Solcast, “Solar data services… in the cloud,” *solcast.com*. solcast.com.

[56] Alliance for Rural Electrification, “Studer Innotec - Electrification of the Mpale village (Tanzania),” *ruralelec.org*. https://www.ruralelec.org/project-case-studies/studer-innotec-electrification-mpale-village-tanzania.

[57] CEIC Data, “Zambia Monthly Earnings,” *ceicdata.com*, 2021. https://www.ceicdata.com/en/indicator/zambia/monthly-earnings.

[58] W. Zhang, Y. Wang, J. Wang, Z. Zhang, and Z. Wang, “Reducing kitchen gas consumption by designing a heat gathering shield with guide rings for a domestic gas stove,” *Energy Build.*, vol. 296, p. 113384, Oct. 2023, doi: 10.1016/j.enbuild.2023.113384.

[59] wind-turbine-models.com, “Bonus B23/150 Gittermast,” *wind-turbine-models.com*, 2011. https://en.wind-turbine-models.com/turbines/189-bonus-b23-150-gittermast.

[60] S. Whittaker, “Exploring Africa’s untapped wind potential,” *Global Wind Energy Council*, 2020. https://gwec.net/wp-content/uploads/2021/04/IFC-Africa-Wind-Technical-Potential-Oct-2020-1.pdf.