Preliminary design and analysis of a proposed solar and battery electric cooking concept: costs and pricing

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November 2015

This report has been produced by Centre for Environmental Strategy, University of Surrey, for Evidence on Demand with the assistance of the UK Department for International Development (DFID) contracted through the Climate, Environment, Infrastructure and Livelihoods Professional Evidence and Applied Knowledge Services (CEIL PEAKS) programme, jointly managed by DAI (which incorporates HTSPE Limited) and IMC Worldwide Limited.

DOI:http://dx.doi.org/10.12774/eod_cr.november2015.leachm

First published November 2015

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SECTION 1

Aims, objectives and outputs

The aim for the project is to assess some of the key assumptions around the potential for solar electric cooking as an option for poor households. The overall objective for this study is to give a sense of the likely price evolution of a PV-battery cooker over the next 15 years, and how that compares to traditional cooking with purchased fuels such as LPG (liquefied petroleum gas) or charcoal, with commentary on the sensitivities to different variables. This is the final report of the study and should be read in conjunction with the overall project synthesis report for the broader context of the work.

Batchelor (2015) claims that by 2020 the price point for a PV-battery electric cooking system expressed as a monthly amount will be comparable to charcoal expenditure. Seeking to explore this argument, the specific research question is: given the trends in pricing in Solar Photovoltaic panels, lithium ion batteries and charcoal/wood pricing in Africa, will there be a point when a suitably appropriate use of solar panels combined with battery, hot plate, control panels, with/without inverter could create a cost effective Solar Electric Cooking system which would substitute for charcoal (and wood) consumption for the same lifetime expenditure?

This is an initial study, helping to justify and to scope out a larger research effort. As such, we have not undertaken comprehensive literature reviews nor identified and gathered all relevant data. The approach was to identify the key system components and seek information to allow us to put sensible ranges on parameter estimates for those, and how they might change over time. We bring these together through spreadsheet models of cooking costs for the PV-Battery and conventional systems, explore the sensitivities to parameter uncertainties, and compare the costs for the new and conventional systems.

This report is the final output for the study. It includes the system characterisation and parameterization; an outline literature review, identifying key sources, the data used and brief commentary; a brief description of the spreadsheet model; tables and graphs of results for the costings and the sensitivity analysis, with commentary; identification of key future research questions.

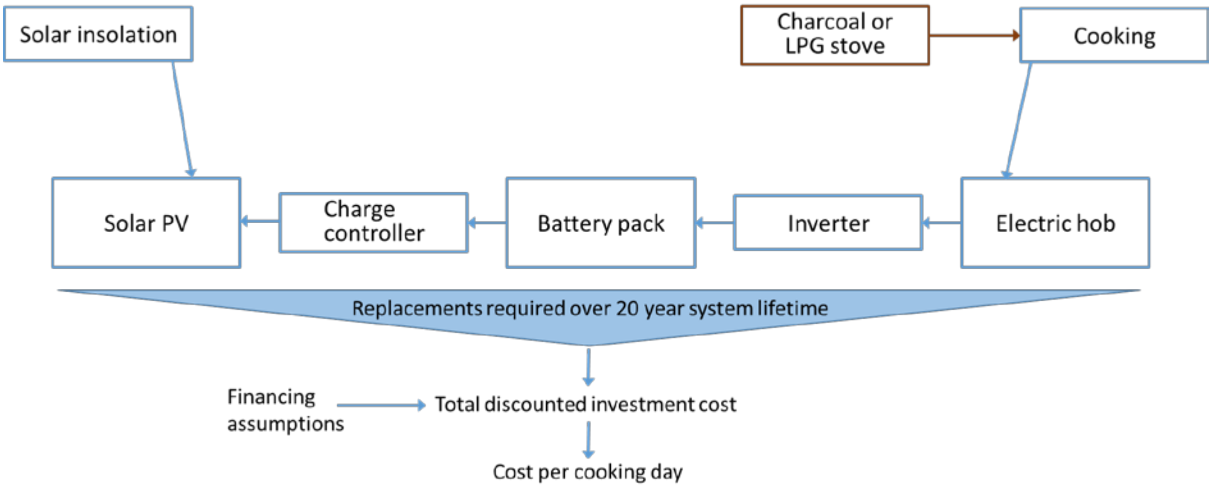
SECTION 2

Outline of the cooking system to be assessed

As a starting point for the research we conceptualise the system as in Figure 1; the arrows indicate the order in which components need to be selected and sized. The study has two starting points: the current cooking patterns or practices that need to be delivered and the solar energy resource available to be used.

Following Figure 1, the energy needs for cooking defines the requirements of an electric cook stove and a matching inverter. The battery storage capacity can then be determined along with a charge controller. Finally, the solar PV can be sized, based on the daily need for battery charging and the solar insolation available. Appropriate information is thus needed on each of the elements in this system, firstly for the system design and sizing, and then for costing.

Figure 1 Cooking system components and parameters



It is important to note that this report is essentially about alternative ways to deliver the 'cooking service' currently delivered by Charcoal or LPG stoves; as such, the important metric is not cost per unit of electricity delivered from this solar powered system, but is related to the cost per meal. As will be seen later, we develop a standard service to be delivered that is based on cooking two hot meals a day for a family of four people. The key metric used is the monthly cost of meeting this need, as this can be compared easily with data on typical charcoal or LPG monthly expenditures.

SECTION 3

Literature review and data sources

The literature review broadly follows the structure of system components identified in the previous section. We had a good start provided by the initial work undertaken by Gamos, in terms of literature gathered and analysis of key parameters (eg Batchelor, 2013; Batchelor and Scott, 2013; Batchelor, 2014; Batchelor, 2015b). Particular parts of this are already strong, such as the exploration of PV and battery price trends (eg Batchelor & Smith, 2015; Batchelor & Smith, 2015b). However, much of this dates from 2014, and at the least required updating.

The steps taken were to: catalogue the existing material; identify updates required; identify evident gaps; and then to seek additional material, making use of databases of published research, grey literature from key international organisations and personal communication with key research groups. Given the resource constraints, this cannot form a 'systematic review', and decisions were made throughout, with guidance from the peer reviewer and wider project team, on when the collected evidence was sufficiently representative.

3.1 Conventional cooking

The modelling approach is to start from an understanding of typical eating and thus cooking practices now, with an assessment of the amounts of conventional fuels used to satisfy that and their costs, before moving on to outline a PV-Battery electric cooking system to substitute. Through evidence in the literature we seek to characterise the daily energy demand for a family's cooking.

3.1.1 Cooking practices and fuels

This section provides a brief review of the cooking practices and key technologies available in Africa, with a focus on users who typically purchase cooking fuel. We explore the use of electricity, charcoal and LPG, with some data also on woodfuel.

More than 80% of Africans cook with solid fuels, with absolute numbers rising. Most households use inefficient traditional cookstoves and the World Bank (2014) estimate that household air pollution from solid-fuel cooking emissions kills nearly 600,000 Africans annually: the second-largest health risk factor in terms of death and disability in the region. Some 7% use Kerosene – also seen as a dirty fuel, with just 11% using 'clean' cooking fuels: 5% use LPG and another 6% use electricity. Significant efforts have been made to develop and distribute improved cookstoves, but it is estimated that only 25% of Africans are using either clean or improved cookstoves (WB, 2014).

As Batchelor (2014) notes, households in Africa and Asia have different choices of energy sources for cooking, depending on their classification. The lack of availability of an energy source, even though a certain group could afford it, affects the choices of cooking fuel. For example, even in countries such as Ethiopia where electricity is cheaper, households in urban areas may have to resort to LPG because of inadequate and unreliable supply of electricity. On the other hand, and particularly true in poor rural communities, access to modern fuels is severely limited by both affordability and availability. Sepp (2014) notes that due to the limitations of relying on one source of cooking fuel households resort to fuel stacking which improves on their fuel security by diversifying sources.

Cleaner cooking options range from those using modern fuels such as LPG, electricity, or solar energy, to improved versions of cookstoves using solid biomass fuels that are more fuel- efficient or that reduce indoor air pollution by, for example, introducing a chimney. Yet even though there have been a lot of projects disseminating cookstoves, the transition to alternative fuels and non-traditional cookstoves has been slow: the World Bank (2014) observe "three decades of efforts to promote both modern fuels and improved biomass stoves have seen only sporadic success at scale" and that "the penetration of clean cooking solutions remains limited". The IEA (2013) estimate that around 2.5 billion people globally will be without access to clean cooking facilities by 2030, as despite continued substitution away from traditional fuels, these improvements are overtaken by population growth (Table 1).

	Without access to electricity		Without access to clean cooking facilities	
	2011	2030	2011	2030
Developing countries	1 257	969	2 642	2 524
Africa	600	645	696	881
Sub-Saharan Africa	599	645	695	879
Developing Asia	615	324	1 869	1 582
China	3	0	446	241
India	306	147	818	730
Latin America	24	0	68	53
Middle East	19	0	9	8
World	1 258	969	2 642	2 524

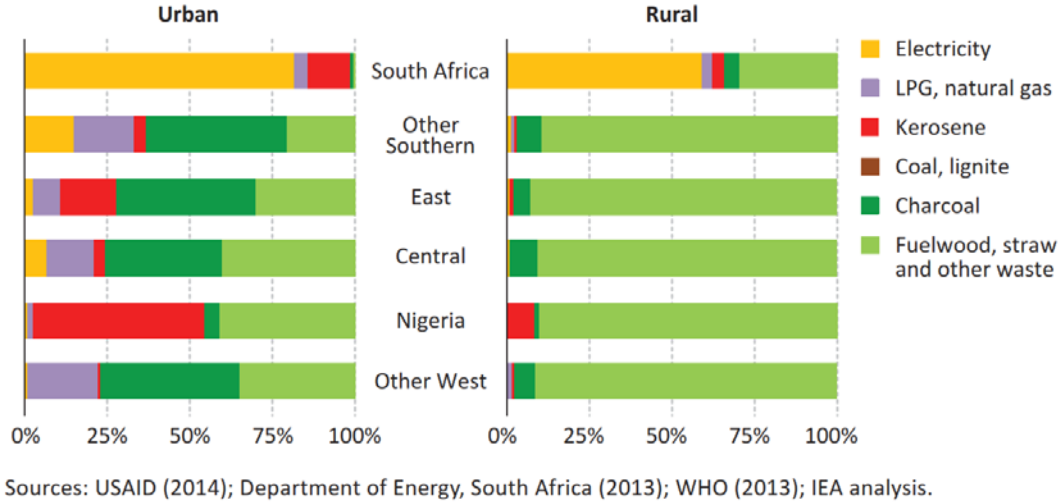
Source: IEA (2013). Note: from the New Policies Scenario

Table 1 Number of people without access to electricity by region (millions)

Figure 2 provides a snapshot of the fuels used for cooking in Africa, and illustrates clearly the differences between urban areas – where electricity, LPG or Kerosene use is widespread, and rural areas where fuelwood dominates in all countries besides South Africa. Charcoal is clearly also important in many urban areas.

The World Bank (2014) provide an in-depth review of the current status of household cooking in Africa. For the purposes of the present study the key aspects are to understand how much energy is typically used to cook, and the costs of delivering that with existing fuels/stoves, such that the case for a competing e-cooker can be reviewed. It is evident that foods eaten, cooking practices, fuels used and stove types vary by country, by location and by context; it is beyond the scope of the study to delve into this variety. Instead we seek to determine a realistic range for each aspect, and explore the sensitivity of the e-cooker's competitiveness.

Figure 2 Main fuel used by households for cooking



Source: IEA (2014)

3.1.2 Energy use in cooking

Ravindranath and Ramakrishna (1997) conducted empirical measurement of the efficiency of various cooking appliances. They undertook both standardised water boiling tests (to the standard VITA protocols in use at the time) but also controlled cooking tests, with housewives cooking a meal for 6 people under controlled conditions, based on rice and sauce. Table 2 summarises the results of the water boiling tests, which comprise boiling and simmering water under controlled conditions and seek to find the basic heat transfer efficiency of the system under test. They specified Percent Heat Utilization (PHU) as the ratio of useful heat delivered to a cooking pot and the total heat content of the fuel used.

Fuel	Device	PHU (%)	Standard development
Dung cakes	Traditional three-pan	11.1	2.9
Firewood	Three-stone fire	15.7	0.3
Firewood	Traditional three-pan	14.2	1.5
Firewood	Swosthee	32.8	1.7
Firewood	ASTRA three-pan	34.0	0.9
Charcoal	Traditional	23.2	0.6
Sawdust	Swosthee	30.4	0.9
Biogas	KVIC burner	45.1	1.4
Kerosene	Nutan	60.2	1.5
Kerosene	Perfect	40.4	2.5
LPG	Superflame	60.4	0.7
Electricity	Hotplate	71.3	2.1

[a]The PHU given is the mean of three tests. The following conversion factors have been used in this study: dung 14.5 MJ/kg, firewood 16.5 MJ/kg, sawdust 13.2 MJ/kg, charcoal 28.5 MJ/kg, biogas 22.2 MJ/m^3, kerosene 44.5 MJ/kg, LPG 45.9 MJ/kg and electricity 3.6 MJ/kWh.

Source: Ravindranath and Ramakrishna (1997). Note: 'Standard development' should read 'Standard Deviation'; we believe this is an error in the original journal paper. The authors note that the standard deviations were all small.

Table 2 Percent Heat Utilization (PHU) in twelve fuel-device combinations

Table 3 summarises the results of the cooking tests. The first column indicates the mass of fuel used per person to cook the meal, which is then converted into energy units.

Fuel–device	Per capita fuel requirement In physical units (g/meal)	(kg pa)	In energy unites (MJ/meal)	(GJ pa)	Mean specific fuel consumption g fuel/kg cooked food	MJ fuel/kg cooked food
DNGTRD	404	295	5.9	4.3	305	4.4
WD3ST	291	212	4.8	3.5	217	3.6
WDTRD	361	263	5.9	4.3	271	4.5
WDSWS	247	180	4.1	3.0	183	3.0
WDASTR	196	143	3.2	2.3	141	2.3
CHARC	124	90.4	3.5	2.5	95	2.7
SWDSWS	330	241	4.4	3.2	253	3.3
BGAS	0.07 m^3	50.9 m^3	1.7	1.2	0.06 m^3	1.3
KNUT	33.7	24.5	1.5	1.1	26.2	1.17
KPER	36	26.3	1.6	1.2	26.7	1.19
LGP	27.3	19.9	1.2	0.9	20.1	0.92
ELEC	0.24 kWh	180 kWh	0.86	0.6	0.18 kWh	0.65

[a]Assuming two meals per day, the composition of the meal remaining constant. Mean fuel consumption per meal is calculated from three tests. So also the SFC given. Fuel–device combination codes are as follows: DNGTRD = dung cake traditional three-pan; WD3ST = firewood three-stone fire; WDTRD = firewood traditional three-pan; WDSWS = firewood swosthee; WDASTR = firewood ASTRA three-pan; CHARC = charcoal traditional; SWDSWS = sawdust swosthee; BGAS = KVIC biogas burner; KNUT = kerosene nuta; KPER = kerosene perfect; LPG = superflame double burner; ELEC = electric hotplate.

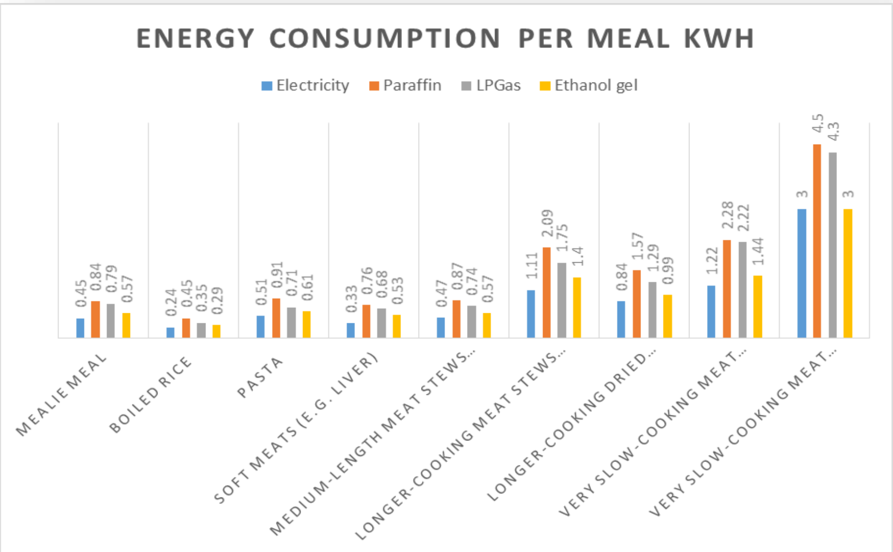
Source: Ravindranath and Ramakrishna (1997).

Table 3 Mean per capita cooking fuel requirement and SFC in Ungra

Ravindranath and Ramakrishna compare the results from the water boiling and cooking tests and conclude that they demonstrate similar relative efficiencies between the cooking types. From a modelling perspective, it is important for us to have a representation of the requirement for energy going into the pot and food – the term ‘Useful Energy’ used in the rest of the current study. Focusing on the middle columns for energy use per meal, we combine the cooking fuel use figures with the Table 2 values for PHU to estimate the useful energy required to cook the meal. The results range from 0.6 to 1.3 MJ per meal per capita, (0.18 to 0.37 kWh), with a mean of 0.9 MJ/capita per meal (0.24 kWh). This equates to 0.72 to 1.48 kWh per meal for a family of four.

As part of an EU-funded project in South Africa, Cowan (2008) conducted similar tests of the energy used by different cooking appliances, both in the laboratory but mainly under real cooking conditions. He explored the cooking energy for a wide range of types of meal.

Figure 3 Consumption by fuels required to cook various African meals



Source: Batchelor (2015), derived from Cowan (2008). Cooking each meal component, for 4 people

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Cowan also assessed the energy use for cooking typical meals, with combinations of the individual components in Figure 3; he gave particular attention to rice plus chicken stew (one of the 'medium length meat stews'). For Table 4 we have combined Cowan's estimates for cooking this meal for 4 people with the earlier estimates of device efficiency, to derive another set of estimates for the useful energy needed to cook a meal.

	Fuel use for cooking for 4 people			Useful energy
Fuel type	**Rice**	**Chicken stew**	**Meal**	
	kWh/meal	**kWh/meal**	**kWh/meal**	**kWh/meal**
Electricity	0.24	0.47	0.71	0.51
Paraffin (aka Kerosene)	0.45	0.87	1.32	0.66
LPG	0.35	0.74	1.09	0.66

Note: useful energy derived from Cowan (2008)'s kWh fuel use and Ravindranath and Ramakrishna (1997)'s PHUs.

Table 4 Useful energy for cooking

The 0.51 to 0.66 kWh per meal for 4 people here compares to 0.72 to 1.48 kWh from the analysis of Ravindranath and Ramakrishna (1997). The difference between the two sets of estimates will reflect: differences in assumptions between the two studies about what constitutes 'a meal'; that one study is of India and one of South Africa, with very different ingredients and cooking needs; and specifically that the Cowan values refer to relatively easy-cooking ingredients. However for the purposes of the current scoping study, the range can be taken usefully to represent a range of end uses for any new cooking system. Table 5 shows the parameter values used in the modelling for this study. Combining the useful energy estimates with the typical 70% efficiency noted above for electric hotplates, the daily electricity demand for a family of four cooking two meals a day is assumed to be 1.46 to 4.23 kWh/day (5.25 to 15.22 MJ/day).

	kWh		MJ	
	Low cook	High cook	Low cook	High cook
Useful energy, meal per person	0.13	0.37	0.46	1.33
Useful energy, meal for 4 person family	0.51	1.48	1.84	5.33
Useful energy, for 2 meals per day	1.02	2.96	3.67	10.66
Electricity demand, assuming 70% efficiency	1.46	4.23	5.25	15.22

Table 5 Useful energy and electricity demand cooking assumptions for the study

3.1.3 Fuel prices

The World Bank (2014) note that some 50% of Sub Saharan Africans already pay something for their cooking fuels, with most of the remainder gathering fuelwood in rural areas. There is growing evidence of some willingness to pay for better cook stoves and/or better fuels, although ability to pay remains generally low.

We concentrate on two fuels: charcoal and LPG. As seen in Figure 2, they are widely used in urban areas throughout Africa. They are purchased fuels, and would typically be the competitors for a PV-battery electric cooker in areas where grid electricity is not available, or where supplies are not reliable enough to support electric cooking. This section seeks to determine price per unit for these two fuels and projections of price over time. In doing so we also find evidence on quantities of fuel purchased and household expenditure per month. We also consider estimates of the cost of capital stock (i.e. the cooking appliance itself). Fuel prices are highly variable between countries and sub-regions, and with changes over time influenced by multiple factors. Markets for fuels are affected by government policy (e.g.

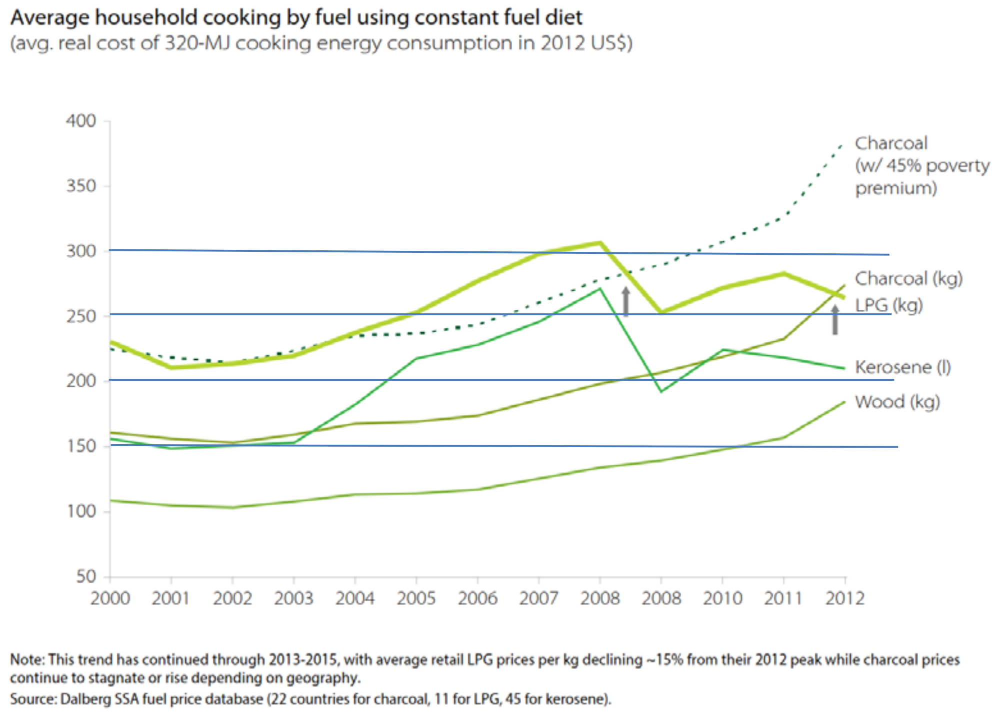
via direct subsidies and other market influences) as well as by global oil and gas prices. As such, it is difficult to establish representative fuel prices and their trends through picking specific prices reported for any one country. For this study we draw on a combination of recent cross-country analysis by the World Bank, followed by exploration of some more detailed fuel- and country- specific evidence.

3.1.3.1 Fuel prices in SSA

Figure 4 shows the trends for the real cost (i.e. adjusted to prices of a constant base year) for cooking with different fuels in Sub-Saharan Africa; these figures reflect a combination of fuelprice trends and assumptions on cooking and stove efficiencies. It is the trend that is of interest here, reflecting the historical average for SSA of fuel prices in real (i.e constant year) terms. Charcoal prices have risen across the period 2000 to 2012 at an average of 4.6% per annum and LPG at 1.4%

WB (2014) note that the long term trend of rising prices has continued through 2013 and 2014, but with a spike in fossil fuel prices in 2013-2014 compensated by a 10%-20% price decline for LPG and kerosene in late 2014-early 2015. It is notable that as of 2011, the average cost of charcoal cooking in the region exceeded that of LPG. The difference is even stronger for the urban poor who pay on average a 45% premium as they buy charcoal in small quantities.

Figure 4 Historical Fuel Cost for the Average Household in Sub-Saharan Africa



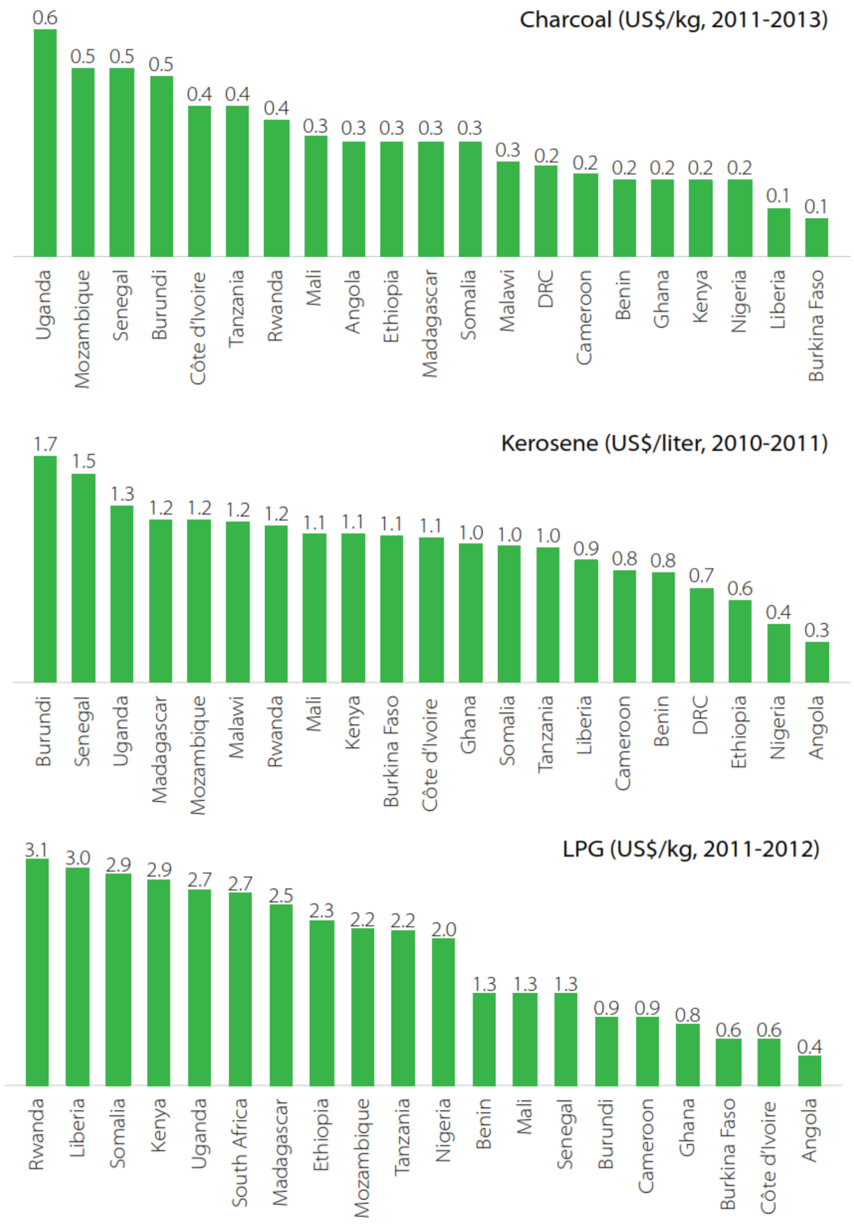
Source: World Bank (2014)

The different trends for Charcoal and LPG reflect various local and global factors. For Charcoal, the Energy Commission (2015) in Ghana note that dealers explain rising prices coming from high transport costs and the poor state of roads from production areas. The relatively slower growth in LPG prices, with declines in recent years, reflect improvements in LPG availability, through market and infrastructure development, but principally reflect global oil and gas price trends.

3.1.3.2 Fuel prices by country

Moving beyond African averages, Figure 5 presents an assessment of fuel prices by country, for the period between 2010 and 2012.

Figure 5 Fuel Prices by Geography



Source: World Bank (2014). Note: various original data sources and hence prices for varying dates

Again, the wide variation in prices reflects many factors, including differences in market size for the various fuels in each country, as well as government policies, including the application of subsidies.

Excluding the extreme outliers, Figure 5 suggests a range of charcoal prices from 0.2 to 0.5 $/kg and LPG from 0.8 to 2.9 $/kg. Government subsidies for retail LPG are common, but practices vary and change frequently, as does treatment of value added tax (e.g. see GACC, 2014). On the assumption that as markets mature and usage grows, LPG subsidies will be removed, we further remove the lower quartile of prices from Figure 5, and thus assume a range of 1.3 to 2.9 $/kg. Projecting these values to estimate 2015 prices, based on the historic trends of Figure 4 and the additional commentary, we assume annual real price prices of 4.6% and 1.4% for Charcoal and LPG respectively and thus estimate the 2015 price ranges: Charcoal 0.23 to 0.57 $/kg and LPG 1.36 to 3.0 $/kg.

3.1.3.3 Charcoal price assumptions

Table 6 shows the charcoal assumptions taken for this study, and the resulting range of estimates of cooking costs under different scenarios.

4 person family, 2 meals per day				
	Low cook		**High cook**	
Useful cooking energy, kWh/day	1.02		2.96	
Charcoal cooking efficiency, %	23.2		23.2	
Charcoal use, kWh/day	4.40		12.76	
Charcoal calorific value, kWh/kg [1]	5.18		5.18	
Charcoal use, kg/day	0.85		2.46	
	Low price	**High price**	**Low price**	**High price**
Charcoal price, US$/kg	0.23	0.57	0.23	0.57
Charcoal cooking cost US$/day	**0.20**	**0.48**	**0.57**	**1.40**
Charcoal cooking cost US$/month	**5.9**	**14.7**	**17.2**	**42.7**

[1] Khider and Elsaki (2012) [2] http://www.xe.com/currency/ghs-ghanaian-cedi

Table 6 Current charcoal cooking cost assumptions

The charcoal cooking efficiency figures were discussed in section 3.1.2; as for all of the fuel/stove types, they were derived from standard water boiling tests. We know that such tests are not a perfect reflection of the messy realities of daily cooking, but they are intended to give some indication of the relative efficiencies. However amongst charcoal, LPG and electric cooking, cooking with charcoal is likely to show the largest discrepancy between standard tests and daily practice, as a charcoal stove is much less controllable than the others. We could expect then that the average efficiency of charcoal cooking will be lower than the 23% given above. We have no specific evidence on which to vary this figure, but in general the results obtained for the cost of cooking with charcoal should be treated as conservative.

Given the wide range of relevant factors, future trends cannot be known with any certainty, but continued annual growth on the historic average of 4.6% (in real terms) is widely used in other modelling (e.g. see WB, 2014, Appendix 6). To explore the sensitivity of the results to uncertainty in fuel price evolution, we adopt low and high growth rates around this value, of 2% and 7% per annum. Table 7 shows how these assumptions of charcoal price trends affect the above scenarios for future cooking costs.

Charcoal	**Low cook low price**	**Low cook high price**	**High cook low price**	**High cook high price**
2015 cooking cost US$/month	5.9	14.7	17.2	42.7
2020 cooking cost US$/month: 2% per annum	6.6	16.2	19.0	47.1
2020 cooking cost US$/month: 7% per annum	8.3	20.6	24.1	59.8

Table 7 Projected charcoal cooking cost assumptions

3.1.3.4 Liquefied Petroleum Gas (LPG)

For the current study, Table 8 and Table 9 show the assumptions about current and future scenarios for LPG cooking costs.

The SSA average price trend for LPG has been +1.4% per year in real terms, although this disguises a 5% per annum increase through the 2000s followed by a 3% per annum decline from 2008. Globally oil prices are currently at low levels, and so in the long term the prospects are more likely for a strengthening of price growth. To explore this uncertainty we adopt real annual growth rates for LPG prices of between 0% and +5%.

4 person family, 2 meals per day				
	Low cook		High cook	
Useful cooking energy, kWh/day	1.02		2.96	
LPG cooking efficiency, %	60		60	
LPG use, kWh/day	1.70		4.93	
LPG calorific value, kWh/kg (1)	12.78		12.78	
LPG use, kg/day	0.13		0.39	
	Low price	**High price**	**Low price**	**High price**
LPG price, US$/kg	1.36	3.00	1.36	3.00
LPG cooking cost US$/day	**0.18**	**0.40**	**0.53**	**1.16**
LPG cooking cost US$/month	**5.5**	**12.1**	**16.0**	**35.2**

(1) http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,20041&_dad=portal

Table 8 Current LPG cooking cost assumptions

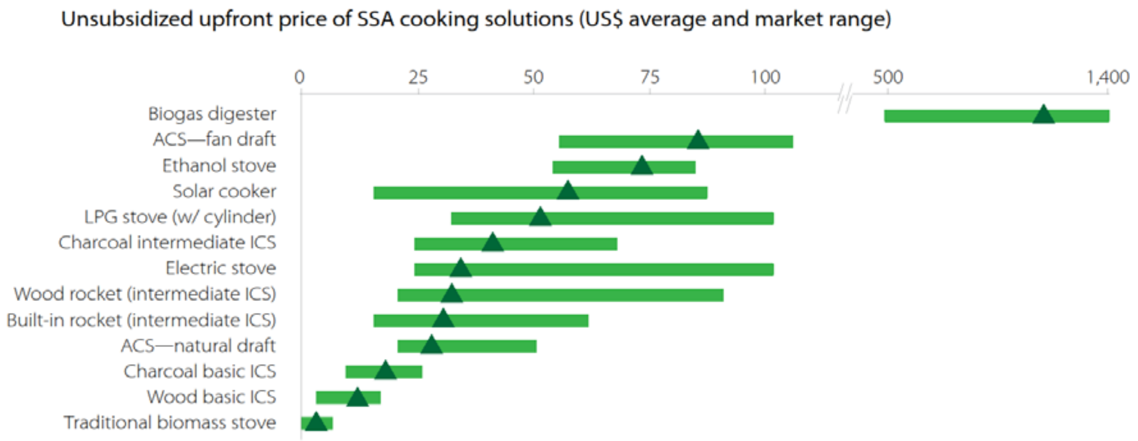
LPG	**Low cook low price**	**Low cook high price**	**High cook low price**	**High cook high price**
2015 cooking cost US$/month	5.5	12.1	16.0	35.2
2020 cooking cost US$/month: 0% per annum	5.5	12.1	16.0	35.2
2020 cooking cost US$/month: 5% per annum	7.0	15.5	20.4	45.0

Table 9 Projected LPG cooking cost assumptions

3.1.4 Cost of conventional cooking appliances

This section reviews prices of stock appliances used for the various cooking methods.

Figure 6 Stove costs in Africa (2012)



Source: World Bank (2014). Note: the triangles mark Africa-wide averages

3.1.4.1 Charcoal stoves

Charcoal cooking makes use of a stove or coal pots as the main appliance. There has been an evolution of different types in the quest to achieve fuel efficiency and cost efficiency by reducing heat loss and improving air control. Different African countries have different stoves or cookers that use charcoal. For example there are significant energy gains in the use of the orange metallic stoves in Uganda and Kenya with a reported 55% reduction in the quantity of charcoal used. An article on efficient Ugandan charcoal stoves (Luganda, 2013) provides costs of small, medium and large stoves as 5,000 shillings (US$6), 25,000 shillings (US$10) and 30,000 shillings (US$12) respectively. In Ghana, the traditional stove tagged coal-pot is cheaper and less efficient than the recent Gya pa-Coal pot. The former has a price range of GHC15-GHC30 (US$4-US$8) while the latter's price is between GHC35 to GHC50 (US$9-US$13).

3.1.4.2 LPG Appliances

We began with a search on literature for data on prices of gas stoves, cylinders and regulators in Africa. Based on the difficulty of finding recent data, surveys on retailer websites and retail shops were conducted. The scope of the survey was thus not wide. However, the range of prices in Nigeria, Ghana, Kenya, South Africa and Uganda could be adequate to illustrate the current prices of gas cookers.

The use of natural gas or LPG is possible with different types of cook stoves. The stoves are made mainly of steel and a small part of glass and other materials and come typically with one, two or four burners. In this investigation, only one and two burners were considered which is in line with most African cooking where a maximum of two stoves are used. (One for the sauce and the other for the main meal). 15 years was estimated to be the life time of the stoves as applied in Jungbluth (1997).

The cylinder which is the container for the gas comes in various sizes of 6kg, 10kg, 13kg and 15kg, above which are used for industrial purposes. We use the 15kg for our analysis since it is popular with households. General surveys report that a 15kg of LPG can serve a household for 5 weeks: this is broadly consistent with the assumptions and calculations made in Table 8.

Regulators and valves are used for the control of gas flow from the cylinder to the gas stoves. For safety reason, they are usually checked after every refill but should be changed after four years. They come in different brands with less variation in pricing. Checking of the hose or tube connecting the cylinder and gas stove is as important as that of the regulator. Most gas filling companies recommend changing the tube at least once in a year.
Table 10 gives price ranges for the different components of the LPG cooking system. The burner costs are similar to those for improved cook stoves using charcoal or wood. A difference is the need to buy a cylinder when you first start using LPG; thereafter you pay just a fuel cost for a refill. The fixed costs will be overshadowed by the fuel costs rapidly; in the analysis we focus on LPG fuel costs.

LPG	Price Range($)	Average price($)
Cylinder (15kg) for Household	32.00-34.00	33.00
Regulator	5.30-8.00	6.60
Cooker		
2 Burner	21-27	24.00
1 Burner	10-14	12.00
Survey area	Ghana, South Africa, Nigeria, Uganda and Kenya	

Table 10 LPG cooking appliance costs

3.2 Solar PV

3.2.1 Solar insolation and PV output

3.2.1.1 PV performance

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 (JRC, undated a). 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.

3.2.1.2 System sizing approach

For a large scale PV installation, very careful positioning of panels, for orientation, to avoid shading and to ensure sufficient airflow to keep operating temperatures low, is a standard part of design and installation. For the PV-battery cooking application, it is similarly important, but perhaps more challenging, to ensure this careful siting of the PV unit. For the core analysis we will size to optimal siting, but then explore the sensitivity of the system design (primarily the sizing of the PV to achieve the required daily electricity output) to a range of assumptions about PV mounting and thus performance.

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 scoping study, 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 principle means of cooking, or with a smaller PV, capable of producing sufficient power only in sunnier periods. The latter might work perfectly well for some households: as discussed earlier, fuel 'stacking' is already a common feature as people move from conventional cooking practices. 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, as seen in Table 11 for two sample locations in Kenya and Tanzania. For the core of the present study we have sized the system such that it should operate year-round, and explore alternatives in sensitivity analysis.

The EU's PVGIS project (JRC, undated b) 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 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 study we have used the PVGIS tool to produce a series of 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), highlighted in the tables.

3.2.1.3 Insolation and PV output data

The results for two runs of the PVGIS tool are in Table 11. The variations made in input values are for location, and setting 'other losses' to zero, as these losses are accounted for separately in our model. Default values are accepted for system-specific loss factors and with location-specific loss factors and optimum values for inclination and orientation calculated within the tool.

The key output is E_d kWh/day. This represents the equivalent number of hours in an average day for which a 1kWpeak panel is operating at that peak output (sometimes referred to as 'sunshine hours'), multiplied by a combined loss factor. The system sizing therefore uses 4.69kWh per day.

(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)

Source: JRC (undated b)

Table 11 PV output from PVGIS model

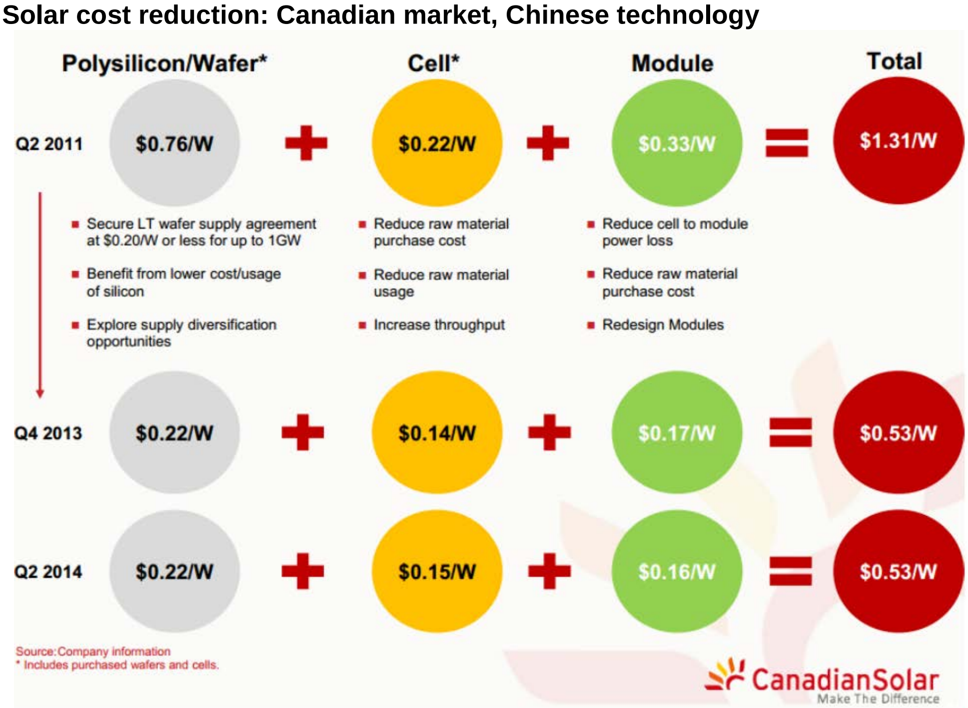
3.2.2 PV costs

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.

3.2.2.1 Cost structure for PV modules

The PV module's price is determined by raw material costs, particularly silicon wafer prices, cell processing/manufacturing and module assembly costs. It is important to distinguish between prices for cells, modules and BoS: the literature contains numerous analysis of historic and potential future trends, and many of these are unclear if they cover one or all of these components. Some of the reported data on rapid cost reductions for solar concerns cells, and the cost reductions for modules may not be as rapid/deep (Deutsche Bank, 2015). Figure 7 illustrates this point: the three components of the PV system are shown horizontally, and the trends for each are shown vertically. The results illustrate that the costs of the PV module (e.g. the casing) have halved in three years, whilst the constituent PV wafer declined by a factor of three. The figure also shows that the total module cost was US$0.53 per Wpeak.

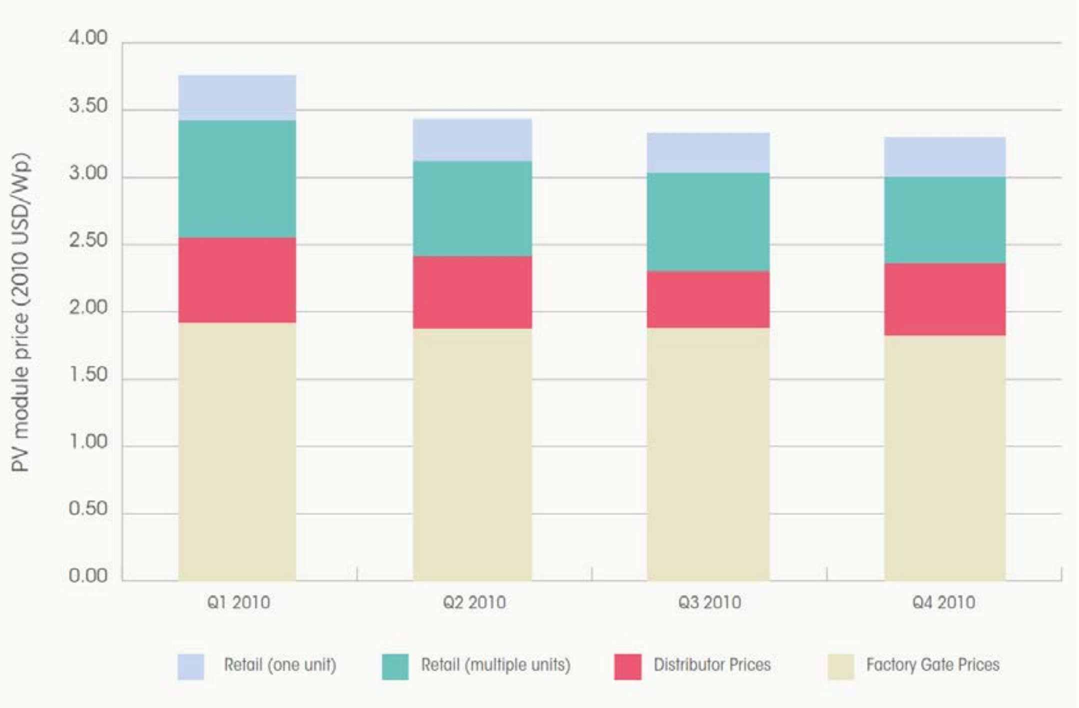
Figure 7 Solar cost reduction: Canadian market, Chinese technology



Source: Deutsche bank (2015)

There is a further complication to interpreting cost and price trend information for modules. Figure 8 presents analysis of the typical retail price structure of modules. Note that the absolute values here are out of date, but the need to treat factory gate prices with caution is clear, as oncosts can increase the total by almost 100%. The oncosts for small scale installation in developing countries may well be lower, as high retail markup might be avoided, but the headline figures of low module costs will normally be factory gate prices, and some addition to that must be made to reflect real system costs.

Figure 8 Weighted average retail c-si PV module price levels and structure in 2010



Source: Irena (2012)

3.2.2.2 Historical cost trends for PV modules

IRENA's 2012 working paper on renewable energy technologies provides a very detailed review of past cost reductions, again for complete modules. Figure 9 shows the trend for two PV technologies, conventional c-Si PV modules and thin film cadmium telluride PV technology. The historical price trend exhibits a 22% learning rate, with price reducing by 22% for every doubling of global installed capacity.

Figure 9 The global PV module price learning curve, 1979 to 2015

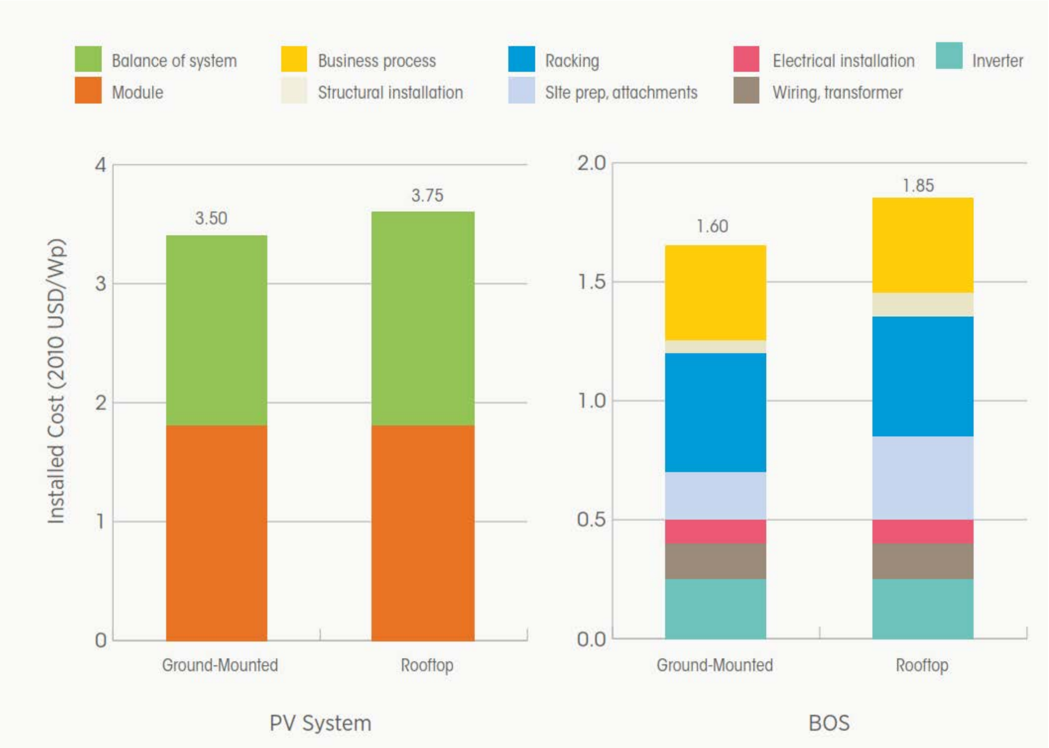
Source: IRENA (2012)

As Deutsch Bank (2015) point out, solar currently comprises only around 1% of the global electricity market; thus there remains enormous growth potential. There are a variety of analyses about the prospects for solar expansion and continued cost reduction. Deutsch Bank (2015) are bullish, expecting a further 40% cost reduction over the next 4-5 years as solar module costs continue to decline, panel efficiencies gradually improve, balance of system costs decline, and solar becomes increasingly mainstream, squeezing markups.

3.2.2.3 Balance of System

The Balance of System components required for a PV application depend on the application. In all cases there will be some wiring. In some applications there will be racking or other mounting costs, for equipment and installation. For applications that are grid connected or otherwise require AC power, an inverter is required. Figure 10 illustrates the typical scale of BoS costs for residential PV installations in the US.

Figure 10 Cost breakdown of current conventional PV systems in the United States, 2010



Source: Irena (2012)

For the current application, we consider there to be low PV mounting (i.e racking) costs, and no site preparation. The PV modules will not be grid connected and thus do not require an inverter (an inverter may be included between battery and cooker, see later), but are connected to batteries via a charge controller, whose characteristics and costs are considered separately, in the section on batteries. Thus the BoS is treated here as compromising simply wiring costs, estimated at adding 10% to the module costs.

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3.2.2.4 Study assumptions on PV costs

Based on the above discussion, we adopt a set of estimates for PV costs, shown in the figure below, and will explore sensitivities to these values. It has been widely reported that PV costs have fallen to around 0.5$/Wp this year. As demonstrated above, this is a factory-gate module cost figure, and for any application the full cost of the PV part of the system will be significantly higher. We assume here that the markup from factory gate module costs is 40%.

Year	**Total price**	Module (factory gate)	Other BoS	Sales
	$/Wp	$/Wp	$/Wp	$/Wp
2014	**1.01**	0.65	0.10	0.26
2015	**0.85**	0.55	0.08	0.22
2016	**0.81**	0.52	0.08	0.21
2017	**0.76**	0.49	0.07	0.20
2018	**0.71**	0.46	0.07	0.18
2019	**0.67**	0.43	0.06	0.17
2020	**0.62**	0.40	0.06	0.16

Table 12 Assumptions on PV system costs

3.3 Battery system[1]

3.3.1 Battery cell types

Efforts in battery development, notably for Lithium-ion types, in the past five years have focused largely on the nascent 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)

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, as illustrated in Table 13. Detailed discussion of different battery types is out of scope for this work. However in the sections that follow, data from the literature is used to specify performance characteristics for current and possible future storage. We will seek to specify a generic storage system with a range of values for key parameters, reflecting in part differences between possible future technologies. A key message is that there will continue

1 The following represents a relatively simplistic view of battery technology and system sizing, drawing on the literature, seeking a characterisation of the battery for initial system modelling. More detailed consideration of battery options and issues is conducted for this project’s RQ2

to be considerable uncertainty over technical performance and costs for batteries, as these can change significantly between chemistries.

	Cathode	Anode	Electrolyte	Energy density	Cycle life	2014 price per kWh	Prominent manufacturers
Lithium iron phosphate	LFP	Graphite	Lithium carbonate	85-105 Wh/kg	200-2000	USD550-USD850	A123 Systems, BYD, Amperex, Lishen
Lithium manganese spinel	LMO	Graphite	Lithium carbonate	140-180 Wh/kg	800-2000	USD450-USD700	LG Chem, AESC, Samsung SDI
Lithium titanate	LMO	LTO	Lithium carbonate	80-95 Wh/kg	2000-25000	USD900-USD2,200	ATL, Toshiba, Le-clanché, Microvast
Lithium cobalt oxide	LCO	Graphite	Lithium polymer	140-200 Wh/kg	300-800	USD250-USD500	Samsung SDI, BYD, LG Chem, Panasonic, ATL, Lishen
Lithium nickel cobalt aluminum	NCA	Graphite	Lithium carbonate	120-160 Wh/kg	800-5000	USD240-USD380	Panasonic, Samsung SDI
Lithium nickel manganese cobalt	NMC	Graph-ite, silicon	Lithium carbonate	120-140 Wh/kg	800-2000	USD550-USD750	Johnson Controls, Saft

Source: Based on Jaffe, S. and Adamson, K.A. (2014)

Source: IRENA (2015). Note: we believe that the description of the Electrolyte as 'Lithium Carbonate' in this original source is technically incorrect, but this does not affect our use of the table

Table 13 Lithium-ion subcategory characteristics

3.3.2 Battery technical specifications

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. It is thus beyond the scope of the report to try and identify precise relationships between the factors and thus to produce a model of the battery system. Instead, the evidence will be assessed to identify key characteristics and realistic ranges of values for each parameter will be determined, through which sensitivity analysis of the performance and costs of the system can be performed).

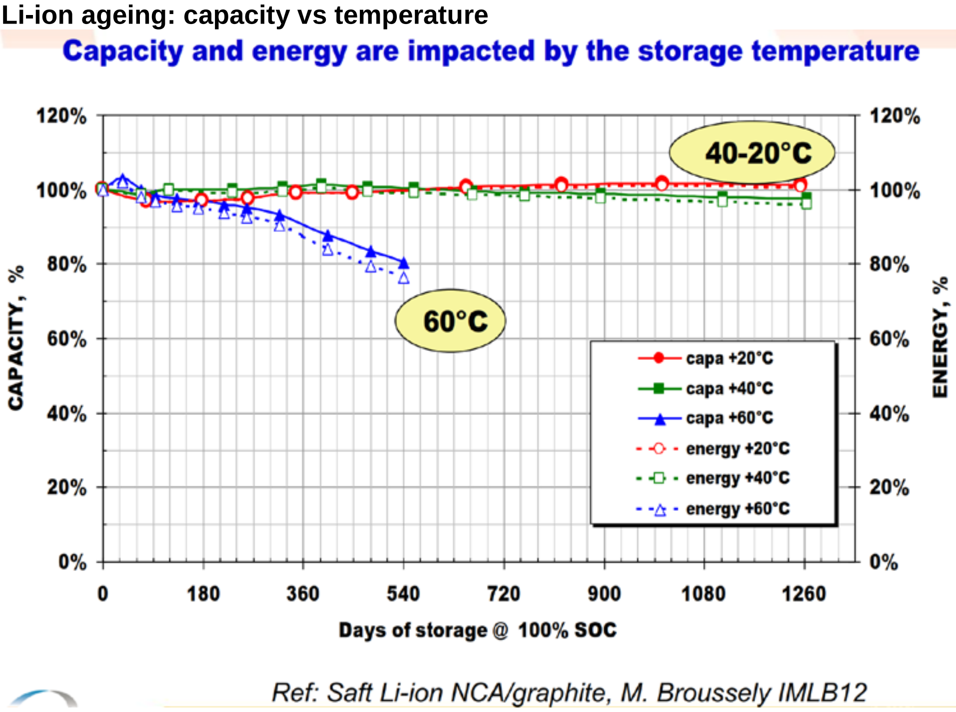
In drawing evidence on battery system performance and costs from the literature it has become evident that careful interpretation is required, as the relevant contexts for figures quoted are rarely given, and then inappropriate use is frequently made of those figures in other sources. For example, Shahan (2015) note that the kWh rating for storage capacity typically provided by manufacturers for batteries is simply the maximum amount of electricity they can store at one point in time. To arrive at a realistic value for the amount of energy that can be retrieved from a battery you have to multiply that capacity rating by a depth of discharge limit, by an efficiency factor, and by a factor reflecting degradation of storage capacity over time. The following sections seek to bring together data from a series of recent reports on batteries to arrive at a reasonable description of performance now and in the future.

3.3.2.1 Calendar and cycle life

Batteries have a finite life due to chemical and physical changes. Two different cumulative processes are usually considered: calendar life ageing - effect of time and temperature on performances; cycle life ageing - effect of charge and discharge cycles on performance.

Calendar life is normally defined as the number of years before a battery's storage capability has degraded to 80% of its rated capacity. As Shahan (2015) point out, at this stage the battery may still be useful, but this is the global standard for "end of product life". Naumann et al (2015) also suggest there can be non-linear ageing effects beyond the 80% degradation point, leading to relatively rapid further decrease in performance The primary parameters determining calendric degradation are temperature and time, driving chemical changes in the electrolyte or the electrode surfaces. Figure 11 illustrates the significance of temperature. The Arrhenius law concerning speed of chemical reactions implies that the deterioration rate doubles with every 10°C increase in the temperature at which a battery is kept.

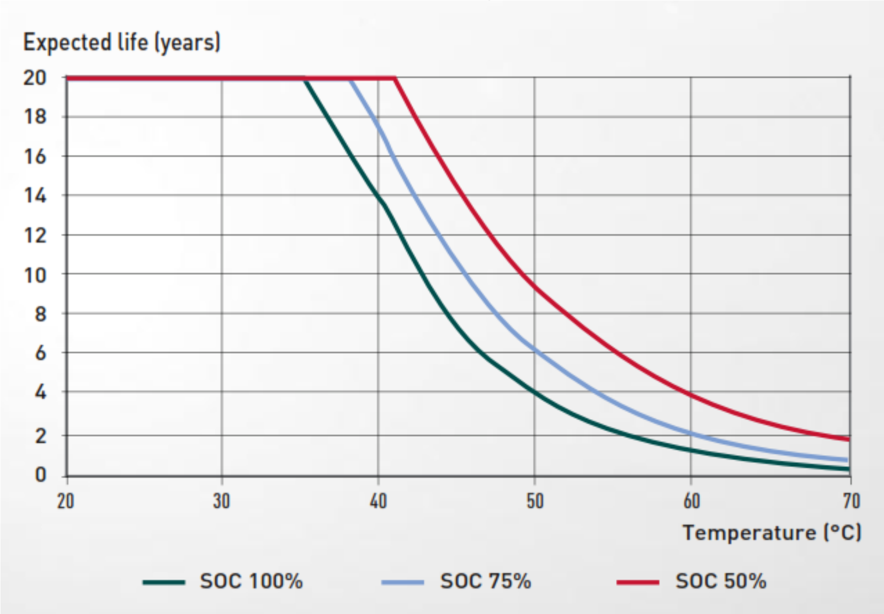
Figure 11 Li-ion ageing: capacity vs temperature



Source: Wiaux and Chanson (2013)

This illustration suggest that there is negligible degradation for temperatures below 40degC (out to 4 years, the extent of testing here). Similar claims are made by various manufactures. For example, for their PV-Li-ion hybrid system Bosch claim negligible calendar loss over 4 years at 25degC and only 10% loss when cells were heated to 55degC (Bosch 2015). Figure 12 presents another battery manufacturer view, for another Li-ion battery in a PV system, which broadly reinforces this point: as long as temperatures are below about 40degC, more than ten years calendar life can be expected. Despite the significance of temperature, the research and commercial literatures are vague about the specific conditions of concern. The mechanisms underlying calendric degradation are complex, but essentially depend on the duration and level of temperatures at which the battery cell exist, whether operating or idle. Higher temperature for longer leads to further degradation. Thus the ambient temperatures where the system is located, and the thermal management of the battery system when charging/discharging are both relevant. In an African context, we can expect ambient temperatures to be in the 20degC to 40degC range; it will be important to ensure that the battery-cooking system is designed to minimise additional heating of the battery coming from the cooking appliance itself, and to facilitate ventilation. For charge/discharge, battery manufacturers are developing more effective thermal management controls, built into battery packs.

Figure 12 Expected life for VL Li-ion calls according to temperature



Source: Saft (undated). Note: end of life corresponds to 20% capacity loss); 'SOC' denotes State of Charge which reflects how much charge is kept in the battery

Calendar life has been a significant issue for batteries in the past, but whilst manufacturer-supplied data must be treated with caution, perhaps the demands of long life products for EV and stationary power markets are driving technical development in cell materials and design, and better thermal management in use, such that it will be insignificant in future. Lithium-ion batteries are generally not as sensitive to temperature as lead-acid batteries (IRENA, 2015) and new chemistries are making further progress. However, the effect of temperature-led degradation could be significant, given that we are seeking to power a heating appliance. The model developed for this study includes a calendar life parameter, and assumptions should explore in particular the influence of shortened life due to high operating temperatures.

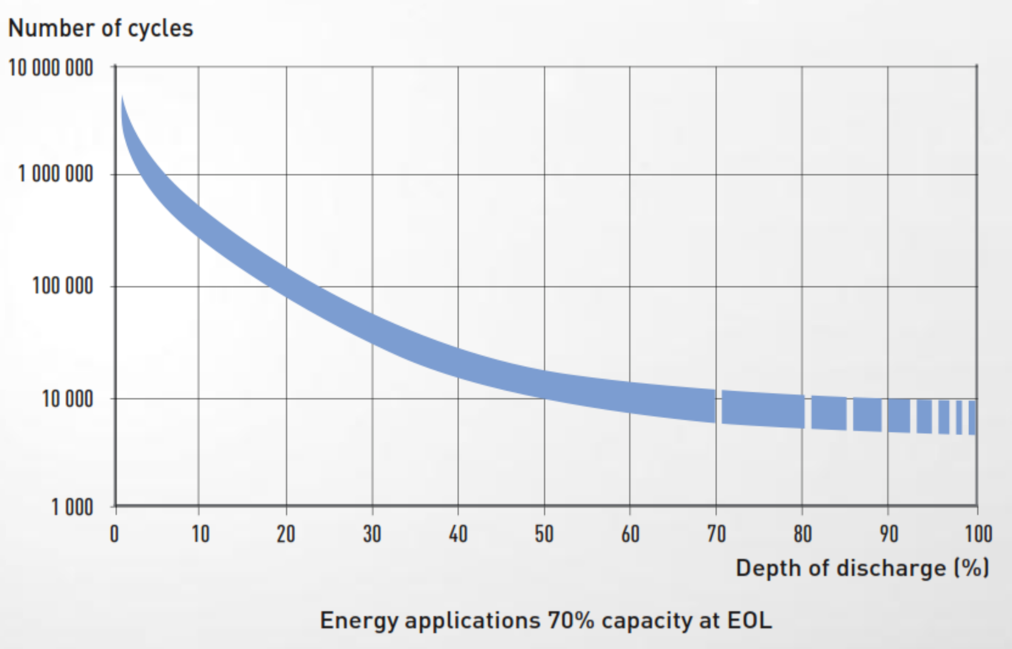
Note that this standard definition of calendar life means that by the end of life, say 10 years, the battery capacity will have dropped by 20%. This capacity reduction has been shown to be approximately linear (e.g. Naumann et al, 2015) and thus for this study will be included as an additional factor in the battery sizing, adding for example 10% to the battery design capacity, seeking to deliver good system performance through the mid-life of the system, with slight tail off towards the end of the calendar life.

The cycle life of a battery is the number of charge and discharge cycles a battery can complete before losing considerable performance (IRENA, 2015). The necessary performance of a battery depends on the application and relative size of the installation. However, a fully charged battery that can only deliver 60-80% of its original capacity may be considered at the end of its cycle life; 70% is typically used. Cycle life has to be specified at a certain depth of discharge and ambient temperature, as these have a strong effect.

3.3.2.2 Effect of Depth of discharge

The depth of discharge refers to the percentage of the rated capacity of the battery that is routinely discharged. The deeper a battery's discharge, the shorter the expected life time (IRENA, 2015). Ongoing developments in cell chemistries and battery management are extending cycle life and reducing the sensitivity to temperature and other factors, reflecting growing interest in battery designers and manufacturers in new applications, such as off grid home power. Figure 13 presents one Li-ion battery manufacturer's data, suggesting that greater than 5000 cycles is possible for even 100% depth of discharge (at 25degC).

Figure 13 Cycle life at +25degC



Source: Saft (undated)

Table 14 shows the claims by another battery manufacturer, who are developing a battery chemistry designed for the small stationary power applications and who are giving particular attention to system life, with 3000 to 6000 cycle life, dependent on depth of discharge.

In an academic study developing a model of PV-battery systems, Naumann et al (2015) refer to a wide range of other studies, and tests on domestic PV-battery systems, and explore a similar range of cycle life assumptions, from 3000 to 6000. We thus include a cycle life parameter with values in a similar range, but will test the significance of a shorter life, reflecting possibly less favourable operating conditions. If the cooking system is used daily throughout the year, the number of charge-discharge cycles will be approximately 365 per year, and thus the cycle range above reflects lifetimes of 8 to 15 years. As for calendar life, the expected reduction in charge capacity towards the -30% for end of life will be incorporated by increasing the battery design capacity by a further 15%.

It is not feasible within the scope of this project to develop a model of lifetime against all of the factors above, given in part that we do not consider a specific battery technology. We thus include parameters for battery lifetime (and hence replacement schedule) that are fixed by assumption, to be set to be broadly consistent with the assumed operating conditions. The sensitivity to the lifetime assumptions will be tested.

	Lead Acid	Aqueous Hybrid Ion (AHI)
100% Depth of Discharge Cycle Life	100 to 1,500 cycles	3,000+ cycles
50% Depth of Discharge Cycle Life	500 to 3,000 cycles	6,000+ cycles
Recommended Temp Range for Optimal Life	25°C to 30°C	-5°C to 40°C
Maintenance Requirements	Frequent – terminal cleaning, maintenance cycling	None
Performance at Partial States of Charge	Poor – leads to sulfation failure modes	Robust to any partial state of charge or long duration stands
System Redundancy at 48 V	No redundancy – single cell failure can bring system to open circuit	Batteries at nominal 48 V deliver system redundancy – no single failure can bring string to open circuit
Safety	Caustic sulfuric acid must be contained in event of case breach	Aqueous electrolyte is non-toxic and non-caustic

Source: Aquion (2015)

Table 14 Key performance indicators for Lead Acid and AHI batteries

3.3.2.3 Round trip efficiency

A proportion of the electricity used to charge a cell is not recoverable on discharge. The main cause of loss is the internal resistance of the battery cells during system charging and discharging, causing the battery to heat up. IRENA (2015) suggest typical Lithium-ion batteries have efficiencies of 80-90%. Shahan (2015) reports a variety of manufacturer data on batteries for home energy systems, with Tesla Powerwall at 92%, Aquion Energy S20P at 85% and Iron Edison at 96%.

For this study we include a roundtrip efficiency, with a range of values tested, from 80% to 95%

3.3.3 Battery system sizing

Any small supply system comprising generation and storage will normally be sized to accommodate some interruption of input generation. In the case of a solar PV system, the critical issue is that variability in insolation levels from one day to the next means that on a dull day the PV might not produce enough electricity to meet the daily cooking demand, and thus the stored electricity in the battery will be lower at the end of the day than at the start, perhaps not providing sufficient energy for the next day's cooking. A larger battery will allow storage of more electricity from the PV on sunny days, allowing the system to 'ride through' subsequent dull days. When PV was expensive, it was common to use smaller capacity PV and larger capacity batteries, seeking to smooth out the daily variability in insolation using the battery. As PV costs have fallen, in sunny regions it is now normal to size the PV to produce the full day's electricity needs in a single day, and similarly to size batteries closer to the daily demand level (Sindela, 2012).

It is also assumed that households will retain other forms of cooking equipment and fuels, as backup and to accommodate occasional needs to cook larger or additional meals. Thus there may be little need for very high reliability of the e-cooking system.

A factor describing the storage capacity of the battery with respect to the typical daily cooking energy usage is thus used to explore the trade off between the size and thus cost of the system, and its reliability. This is a user-defined factor, and for the current study it is not based on any particular evidence on preferences of cost versus reliability.

3.3.4 Maintenance

To ensure reasonable battery life, appropriate control of charging and discharging is needed, including attention to thermal management, and balancing of charge across the various cells. Such control needs to be either built into battery packs, or to be included as a controller within the wider system. Beyond this automatic control, Li-ion batteries are expected to need no maintenance: this is certainly the commercial pitch being made by home energy system manufacturers such as Tesla.

3.3.5 Charge/discharge controls

A controller is needed to manage the interaction between the 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.

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. However that analysis would require accurate costings for alternative controllers and a detailed system specification; this is beyond the scope of the current study. However, the benefits of MPPT for application off-grid in Africa may in any case be low. As Solarcraft (undated) note, the maximum power point voltage for PV drops as ambient temperature increases, thus in hotter climates, the PV efficiency loss in using PWM is lower. This study therefore assumes a PWM controller is used, and typical characteristics for such a controller are found from the literature for small off-grid power systems.

All PV controllers need to be sized to cope with the systems voltage and the maximum amount of current that might flow through them (EDCL, undated). 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 normally recommended to oversize the controller by approximately 20% to allow for peak outputs.

The cost of the controller will depend strongly on its rated capacity. For this study we will refer to a range of commercially available controllers once the sizing is done. However, as found for the inverters, there is a wide price range for high power battery charge controllers (e.g. $25 to $150 for 40A rating) reflecting level of features (e.g. degree of battery temperature protection, efficiency etc.) and overall quality and hence expected life. It is outside the scope of this study to investigate this thoroughly, and so a range of controller parameter values will be tested, and further research will be needed.

3.3.6 Storage system costs

Developing clear estimates of current and prospective battery system costs is difficult; IRENA (2015) note that there is at present 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 are relevant. This is not unusual in areas of technology innovation, and we tackle the uncertainty in this study through exploring ranges of cost estimates. As discussed earlier, batteries for Electric Vehicles have received more attention to date than those for stationary power applications, thus it is useful to explore the evidence on the evolution of costs in the EV market before looking for evidence on batteries for PV systems directly. Note that the literature on battery costs focuses on cost per kWh of electricity stored. Battery sizing needs to be done via the Amp-Hour capacity of the battery, and thus these two metrics will be brought together later.

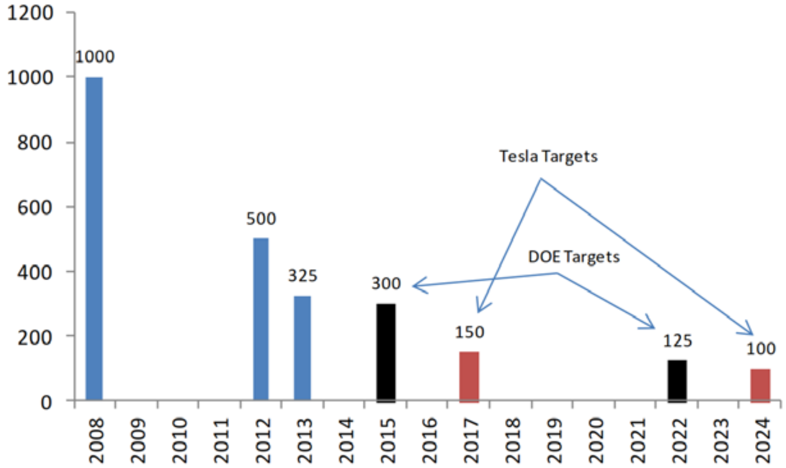
3.3.6.1 Electric Vehicle batteries

Figure 14 brings together a set of estimates of historic cost trends with two sets of future values, reflecting technology development targets published by the US DoE and Tesla. These values are thought to reflect wholesale battery pack costs, and are not specific to any one technology or chemistry.

“Tesla Motors, in partnership with Panasonic, is constructing the ‘Gigafactory’ in Nevada which aims to achieve these economies of scale and better. Tesla estimates that Gigafactory could drive down the cost of its own Li-ion batteries by more than 30% in its first year of production (the factory is scheduled to open in 2017) – which could reduce costs to the ~$150/kWh range. Separately, the US Department of energy has targeted battery cost levels of $300/kWh by 2015 and $125/kWh by 2022.” (DG, 2015).

“We were not surprised by Tesla’s storage product pricing as it is in line with where we see the numbers. However, the $350/kWh product pricing and offering is the installer price not the total price to consumers. Specifically, it does not include the inverter cost, installation costs, and cost of sales.” Shahan (2015).

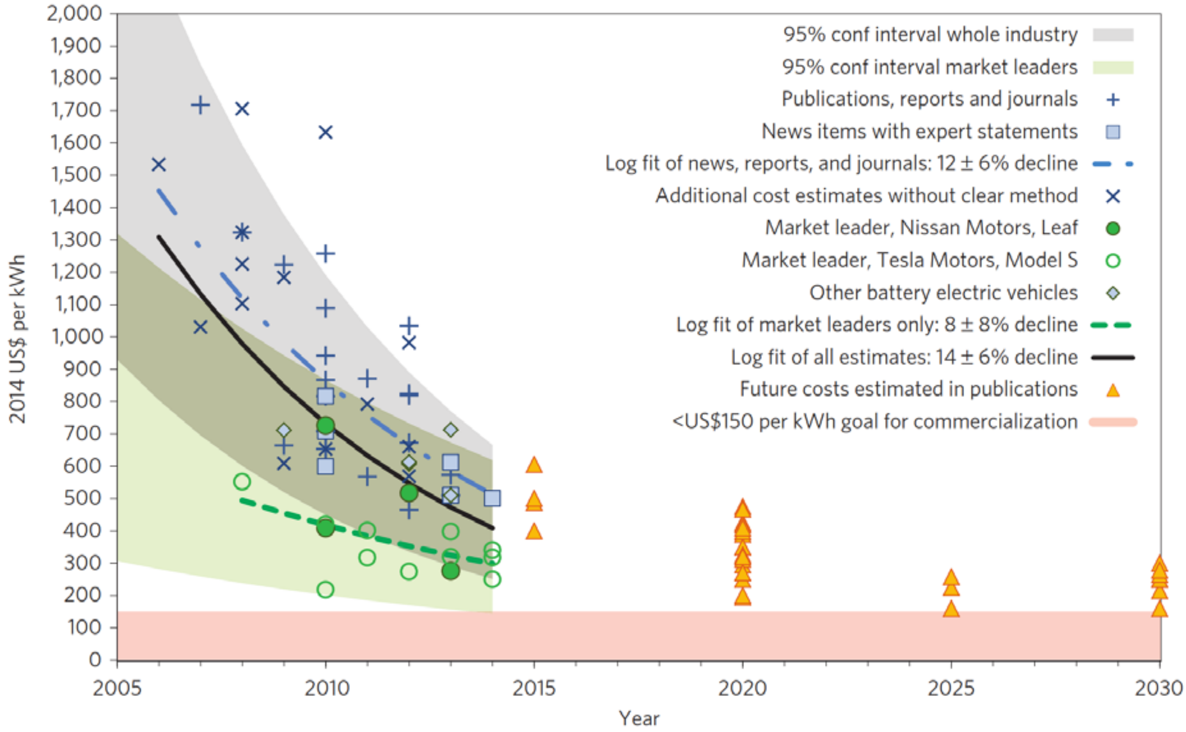
Figure 14 Historical battery prices and future targets ($/kWh)



Source: Deutsche Bank (2015)

As shown in Figure 15, Nykvist and Nilsson (2015) have conducted a major systematic review of battery costs for EV, gathering more than 50 sources, and with careful interpretation of the reported data. Importantly, the costs are reported for batteries and not the constituent cells alone. The study included a variety of cell types, although Li-ion dominate. The study found that the Battery Electric Vehicle market has been doubling annually, and the rate of cost reduction implies a learning rate of around 9% (i.e. the cost has fallen 9% for each doubling of installed capacity. This compares with other estimates of a LR for the constituent cells of more like 16%). They found the current (i.e. 2014) cost range to be US$410/kWh to US$300 /kWh of battery storage capacity.

Figure 15 Cost of Li-ion battery packs in BEV



Source: Nykvist and Nilsson (2015)

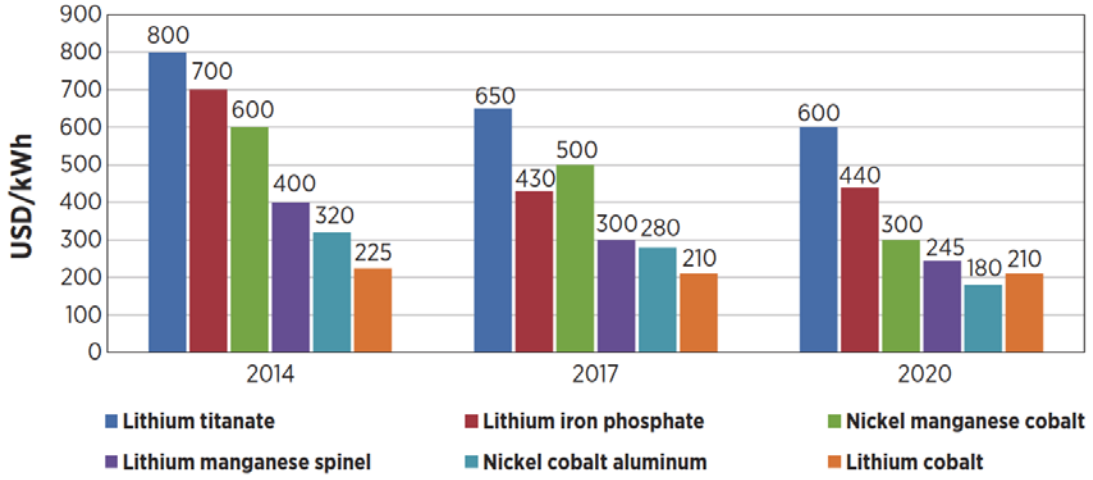
Nykvist and Nilsson caution about the uncertainty in any such analysis, and point to the wide ranges in the data. However in assessing some reasons behind that range (e.g. disparity between market leaders and others) they come the conclusion that it is perfectly reasonable to expect that 2020 costs could reach US$200/kWh and US$160/kWh by 2025.

3.3.6.2 Batteries for stationary power applications

The purchase price of lithium-ion batteries has fallen strongly, and a widely quoted Deutsche Bank report focused on solar PV and battery systems says they expect prices to continue falling by some 20% to 30% per year up to 2020 at least (DG, 2015). Note that this report explores a variety of different storage technologies, and within batteries, discusses a range of different chemistries. Some of their analysis concerns Lithium Ion, but some of the forward projections are agnostic about the chemistry for the batteries that will be in use, which could be Li-I, Li-iron-phosphate, Sodium-Ion, Zinc Air, or other.

Jaffe and Adamson (2014), analysts at the respected industry consultancy Navigant, report on recent cell prices for a range of Li-ion battery types, and make forward projections, shown in Figure 16. These are stated to refer to battery cells not packs or modules. IRENA (2015) suggest that for typical small scale installations, the battery cell represents about 50% of the installed battery system cost.

Figure 16 Lowest cell price of lithium-ion chemistries for utility-scale applications

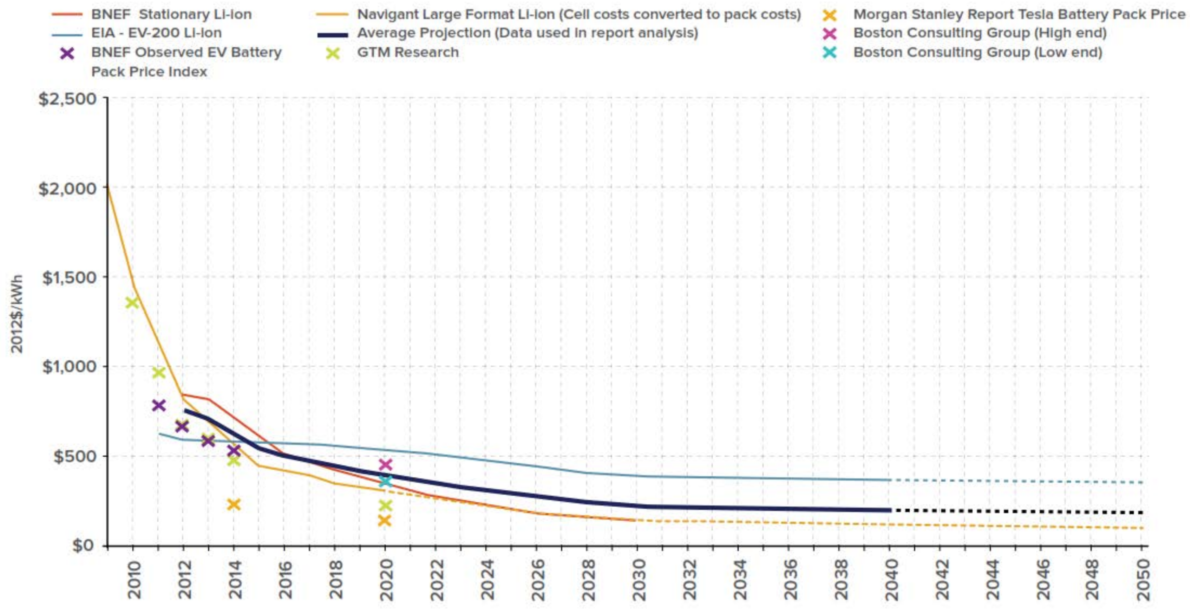


Source: Jaffe and Adamson (2014), reported in IRENA (2015)

Munsell (2014) provides another, broadly consistent, analysis: "Best in class lithium-ion technology was producing commercial/utility packages in the ~$500/kWh range at end 2014 – half the cost of the ~$1000/kWh 12 months prior."

The Rocky Mountain Institute have been conducting a series of studies exploring the costs of moving off-grid within different parts of the USA. As part of their modelling, they forecast solar PV and battery system costs based on a wide literature review, including analyses by investment banks and financial analysts. There is some repetition of sources here, with the data from Navigant likely to replicate that of Jaffe and Adamson (2014) above. However within the scope of the current project it is not possible to refer to all original sources, as the commercial reports are not publicly available. Figure 17 shows the analysis. These figures refer to battery 'packs' rather than cells alone, although it is unclear whether these can be treated as reflecting installation of full storage systems. Also note that the original sources underpinning this chart date from the end of 2013 at the latest.

Figure 17 Lithium-Ion battery pack prices: historical and forecasted



Source: RMI (2015)

In summary, it seems reasonable to estimate the wholesale price of battery packs now at between $300/kWh and $500/kWh, falling into a range of $200/kWh to $300/kWh in 2020. For this study we are modelling key additional parts of the storage system (e.g. the charge controller) separately.

3.3.6.3 Battery pack voltage

Most batteries for off-gird applications come as 12V units. However instead of a 12V battery pack two sets of 12v batteries can be wired in series to provide a 24V battery pack. The immediate advantage is that for any given power output to an appliance (e.g. 1000W to a hotplate) the required current is halved, as Power = Voltage x Current. This allows the use of thinner connecting cables and use of a 24V DC inverter, which will be safer and more reliable. We thus adopt 24V as the design voltage for the battery system.

3.3.7 Battery parameters and values for modelling

The table summarises the parameters and calculations that are used in the model to describe the battery system and its performance. The parameter values shown are chosen to reflect the range found in the literature.

The model here makes a simplifying assumption that the battery voltage is constant (at say its open-circuit level of 24V) under varying load; in practice voltage falls as load increases and thus the current required to deliver a particular level of power output is slightly higher. This is considered further in the work for RQ2, in relation to the practical issues of lifetime and sizing of battery packs.

Parameter	Decription	Units	Value range	
			Optimistic	Pessimistic
F_{store}	Battery number of days storage factor	>=1	1	1.5
$F_{mindepth}$	Battery minimum depth of charge factor	0-1	0.0	0.2
Bvoltage	Battery voltage	V	24	24
Beffi	Round trip efficiency	%	90	85
$Lifebatt_{cal}$	Calendar lifetime of battery	Years	10	5
Bcapaddcal	Additional battery capacity for calendar decay	%	10	10
$Lifebatt_{cyc}$	Cycle lifetime of battery	Cycles	6000	3000
Bcapaddcyc	Additional battery capacity for cycle decay	%	15	15
Bcap	Battery capacity = (ELcookday * Fstore * (1/(Invertereffi/100)) * (1+Losscable/100)) * (1/(Beffi/100)) / Bvoltage / (1-Fmindepth) * (1+ Bcapaddcal /100) * (1+ Bcapaddcyl /100))	Ah	96	190
BWh	Battery capacity = Bcap * Bvoltage / 1000	kWh	2.3	4.6
Battprice	Battery price	$/kWh	200	500
Lifebatt	Overall lifetime of battery, min of calendar and cycle lives	Years	10	5
Costbatt	Purchase cost of battery = BWh * Battprice	$	459	2281

Note: the shaded cells (Bcap, BWh, Costbatt) are calculated values, based on assuming that all of the parameters they depend on take either the 'optimistic' or 'pessimistic' values. In practice a mix of values for the individual parameters will be used for any one scenario in the results section, and thus these calculated values simply give some sense of the most extreme ranges.

Table 15 Assumptions for battery parameters

3.4 Inverter

It is possible to cook by connecting a DC hotplate directly to the batteries. However, to achieve the required power for cooking from the hotplate (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 for the present study, we assume the use of a DC to AC inverter, allowing the use of readily available and low cost AC electric hobs. The other advantage of integrating an inverter is that the user could potentially use the resulting AC power for other purposes: lighting, charging mobile phones, radio/TV etc. Retail prices found for potentially suitable inverters range from US$40 to US$200. This is a wide range; we could not find convincing evidence on inverters in use in similar applications, as the power requirement here is much larger than for other typically small off-grid installations. Given also the trade-off between the additional cost of the inverter and the savings in cooking equipment and wiring costs and losses, this is an aspect of the system design that will warrant further investigation.

3.5 Electric hot plate

Low cost two-ring tabletop electric hotplates are widely available in retail outlets in Africa. Prices in Malawi supermarkets were around $15. We have no data on likely lifetimes, but these are low cost and probably low quality products, and a lifetime range of two to five years seems likely.

3.6 Business model, customer payment plan

The structure of the model is to assess the costs required to deliver the electric cooking service for twenty years, taken as the notional lifetime of the longest lived major component, the PV. The model then includes replacement costs for the other components during that period.

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 the user would make any form of agreement for twenty years. We could explore alternative finance periods, seeking cost recovery more rapidly.

In Section 3 at various points it was noted that the literature is often unclear about the basis of component prices, whether these are factory gate, wholesale or retail. The values used for component costs in our analysis are intended to represent the costs to the cooking service supplier as they assemble the system (ie wholesale). A net present value calculation will then account for the return on investment for the system supplier as they deploy the cookers: by charging the calculated monthly cooking service fee, they secure a return on the investment equivalent to the discount rate used (either 5% or 20% in our scenarios).

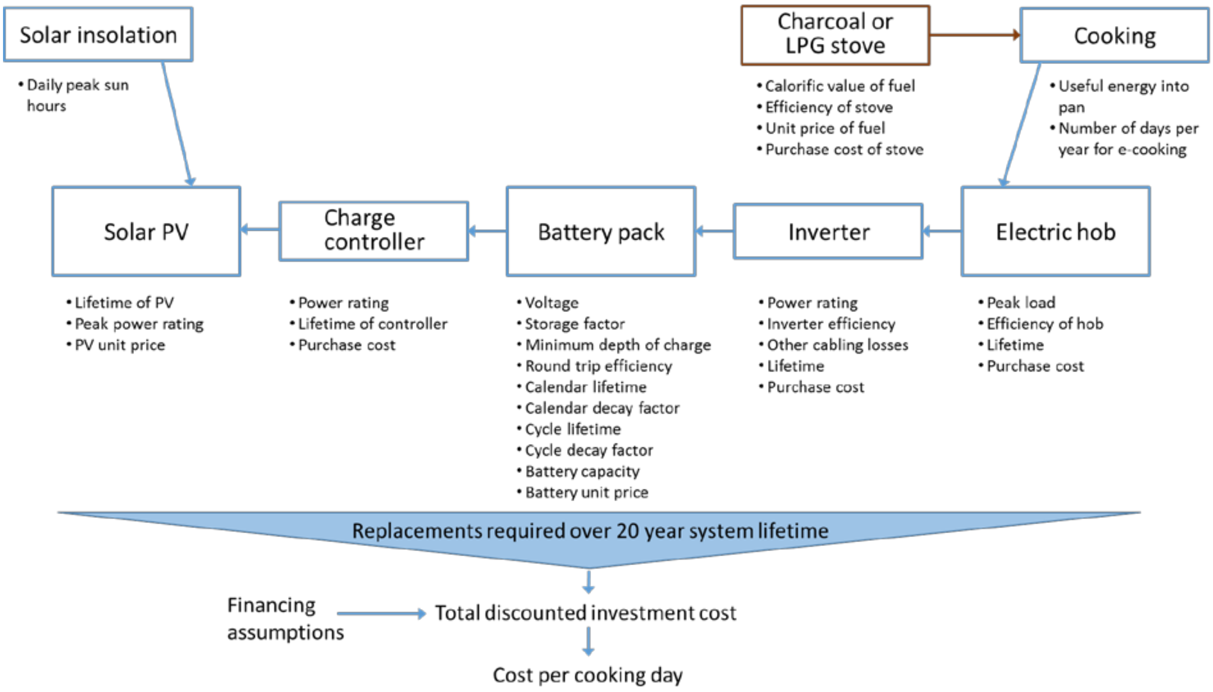
The basis of the service fee calculation is a levelised costing of the cooking service, expressed as cost of cooking per month. Black (1984) provides a useful overview of the approach plus illustrations of different applications. The most common form of levelised costing is that for energy supply, where 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.

SECTION 4

Model outline

A model was developed to size the components for an e-cooking system to meet the specified cooking needs, and to calculate the cost of the system. The model was then used to explore the sensitivity of the sizing and hence of the cooking costs to changes in any of the parameters, reflecting uncertainty, and to simulate changes over time. Figure 18 reproduces the original conceptualisation of the system, with the parameters chosen for the model, based on the literature review. A screenshot of the model, implemented in MS Excel, is given as an Annex, provides another view.

Figure 18 Cooking system parameters



To illustrate the system design process, we give an example, using typical parameter values. A family of four cooks two meals per day, either every day of the year or only in the sunnier half of the year, the daily cooking needs 1kWh of energy delivered into the pan. A 1kW electric hob with efficiency of 70% is used, powered via an inverter with 97% efficiency and with 5% further cabling losses. The battery is sized to deliver the required electricity. It has a minimum depth of charge of 20% and a 10% loss of electricity across charge/discharge cycles. Over its 10 year lifetime, the battery will lose 5% of its effective capacity through ageing and a further 10% through effects of cycling: the battery is sized so that at its mid-life point its effective capacity is sufficient to meet the daily cooking demand. A charge controller is chosen with requisite power output. Finally the solar PV is sized, to meet the daily charge requirement of the battery, given the expected solar insolation in the day.

This treatment of battery degradation as it ages is a simplification for convenience, acknowledging the multiple estimations made in the modelling process and thus uncertainty in the ‘correct’ size for a system. It would clearly not be acceptable to have a cooker that regularly runs out of power part way through cooking a meal. It can be expected that the battery will gradually lose capacity; it could be sized such that the expected remaining capacity at the end if its life is sufficient to meet the normal cooking demand; however it will then be well ‘oversized’ in the early years. We have instead compromised and sized for the mid-life point, with the assumption that the user will make some adjustment to their cooking patterns in later years, to accommodate the reduction in performance.

The cost of the system is then calculated by summing up the capital and operating costs of the components, plus replacement costs for any components that do not last the twenty year life of the PV panel, discounted over the twenty year period.

It is important to note that we assume that replacements are made with components with identical characteristics to those of the initial investment: i.e. we do not allow for technical improvements or cost reductions that might have taken place. This assumption is made for two reasons. Firstly, it simulates the likely scenario that for any particular brand or model of PV-battery cooker there is a limited range of replacement items available in the supply chain, with a slow process of technical improvement and stock turnover. Secondly, this assumption avoids a possible source of ‘technical optimism’, leading to conservative conclusions on the merits of the PV-battery cooker. However in practice the action of discounting of future costs means that including improvements for replacement components would have only a small effect on overall results.

The relationships below show the key calculations in the model.

Cooking
- Daily electricity use for cooking (Wh) = Useful energy into pan / (Effi of stove /100)

Battery
- Battery capacity (Ah) = (Daily electricity use for cooking * storage factor * (1/(Inverter effi/100)) * (1+(cable losses/100)) * (1/(Battery effi/100)) / Battery voltage / (1-min charge depth) * (1+ calendar decay factor) * (1+ cycle decay factor))
- Battery capacity (kWh) = Battery capacity^{Ah} * Battery voltage / 1000
- Overall lifetime of battery: minimum of calendar and cycle lives
- Purchase cost of battery (US$) = Battery capacity^{kWh} * Battery price

PV
- Energy output from PV required (Wh) = Battery capacity^{Ah} * (1-min charge depth) / (1+ calendar decay factor) / (1+ cycle decay factor) * Battery voltage * PV capacity margin
- Peak power rating (sized to min sun periods) (W) = Energy output from PV / Peak sun hours
- Purchase cost of PV (sized to min sun periods) (US$) = Peak power rating * PV price
- Charge controller capacity (PV sized to min sun periods) (A) = Peak power rating / Battery voltage

Costs
- Total capital cost of system (including replacements for 20 year life) = sum of purchase costs of PV, charge controller, battery, inverter, hob
- Net Present value of system = $\sum_{t=1}^{20} \frac{C_t}{(1+r)^t}$ where C_t is costs of all 5 components in year t
- Electric cooking cost per month = Net Present value of system / net present cooking days in 20 years. (Note: Black, 1984 explains the need to discount the units of ‘service’ provided. This can be regarded as a mathematical artefact: we could calculate the cost per unit of service in each year and then discount those back to the present. More conveniently, as here, we calculate the costs per year and discount

those, and then calculate the cooking days per year and discount those, and divide the former by the latter. Mathematically the two approaches are identical).

SECTION 5

Results

5.1 Choice of scenarios

As section 3 shows, there are a wide range of uncertainties in the design, sizing and costing of the system. For the purposes of the main scenarios for this analysis, we distinguish between parameters for which the values are uncertain due to (a) different household cooking practices; (b) uncertainty in technical parameters; (c) changes over time; (d) financing assumptions

(a) *Different household cooking practices:* we distinguish between a daily requirement for 1.02kWh and 2.96kWh useful energy into the cooking pan, reflecting a basic assumption of a four person household eating two hot meals per day, but acknowledging considerable differences in the energy needed to cook different types of food.

(b) *uncertainty in technical parameters*: throughout the system, there is uncertainty in the appropriate value for many parameters. This includes technical performance (such as minimum depth of battery charge and decay rate of battery charge performance with cycling), losses (e.g. through cables and the inverter) and in prices (eg of the PV and battery). Each of these factors could be explored individually, and the ideal approach would be to use a probabilistic method to explore the influence of the uncertainty range for each. The approach taken for this scoping study is to explore the effect of two bundles of values for the technical parameters: an 'optimistic' scenario with better efficiencies and lower costs and a 'pessimistic' scenario with less good technical performance and relatively higher unit costs. The results can then be interrogated to understand the most influential factors.

(c) *Changes over time*: we model the system under the conditions discussed in (a) to (c) above, for 2015 and for 2020. For 2020, we consider some technical improvements (e.g. in batteries) and cost reductions, that will reduce the absolute values and the ranges of uncertainty for many of the system parameters.

(d) *financing assumptions*: we look at the levelised costs of the cooking service, expressed as cost of cooking per month, delivered as a service by an investor who pays for the initial capital and any replacement capital costs over a 20 year period. We investigate the risk attitude of such investors – effectively cooking service providers – by exploring the influence of different discount rates, 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).

5.2 Costs of electric cooking

5.2.1 Scenarios for 2015

Table 16 shows the key parameter values and the modelling results for systems in 2015. The first pair and second pair of numerical columns reflect the different assumptions on low and high cooking practices, as in (a) above. Within each pair, the two columns reflect the range of values according to (b) above, described here as ‘optimistic’ and ‘pessimistic’ assumptions about technical and cost factors. For each system component, the row showing final cost is emphasised. The rows for five key aspects are highlighted: energy for cooking; battery capacity; PV capacity; initial capital cost and overall cooking cost per month.

2015, 5% Discount rate			**Scenario**	**1**	**2**	**3**	**4**
			Parameters	**Optimistic**	**Pessimistic**	**Optimistic**	**Pessimistic**
			Cooking	**Low cook**	**Low cook**	**High cook**	**High cook**
Component	**Parameter**	**Notes**	**Units**				
Cooking	$Euseful_{day}$	Useful energy into pan/food from hob	Wh/day	1020	1020	2960	2960
	Elcookday	Daily electricity use for cooking	Wh	1431	1431	4151	4151
	Lifecook	Lifetime of cooking appliance	Years	5	2	5	2
	Costhob	***Purchase cost of cooking appliance***	***$***	***10***	***15***	***10***	***15***
Inverter	Invertereffi	Inverter efficiency	%	97	90	97	90
	Losscable	Other cabling losses	%	5	15	5	15
	Lifeinverter	Lifetime of inverter	Years	10	5	10	5
	Costinverter	***Purchase cost of inverter***	***$***	***40***	***80***	***40***	***80***
Battery	$F_{mindepth}$	Battery minimum depth of charge	0-1	0.0	0.2	0.0	0.2
	Bvoltage	Battery voltage	V	24	24	24	24
	Beffi	Round trip efficiency	%	90	85	90	85
	$Lifebatt_{cal}$	Calendar lifetime of battery	Years	10	5	10	5
	$Lifebatt_{cyc}$	Cycle lifetime of battery	Cycles	6000	3000	6000	3000
	Lifebatt	Overall lifetime (min of cal. & cycle lives)	Years	10	5	10	5
	Bcap	Battery capacity	Ah	90	140	260	406
	BWh	Battery capacity	kWh	2.2	3.4	6.2	9.8
	Battprice	Battery price	$/kWh	300	500	300	500
	Costbatt	***Purchase cost of battery***	***$***	***645***	***1680***	***1872***	***4876***
PV sizing	Epvday	Energy output from PV required	Wh	1721	2151	4993	6241
	$Peaksunhours_{min}$	Average daily peak sun hours	Hours	4.69	4.69	4.69	4.69
	Pvpowmin	Design peak power rating	W	367	459	1065	1331
	Pvprice	Purchase price of PV per Wp	$/Wp	0.85	0.85	0.85	0.85
	CostPVmin	***Purchase cost of PV panels***	***$***	***312***	***390***	***905***	***1131***
Charge controller	Cccapmin	Charge controller capacity	A	15	19	44	55
	Lifecontrol	Lifetime of controller	Years	15	5	15	5
	Costcontrolmin	***Purchase cost of controller***	***$***	***25***	***100***	***25***	***100***
Overall costing	r	Discount rate		5	5	5	5
	Costinitial	Initial purchase cost of system	$	$1,032	$2,265	$2,852	$6,202
	Costsystemmin	Total cost of system (over 20yrs)	$	$1,772	$7,965	$4,820	$21,488
	$Ecookcostmin_{month}$	**Electric cooking cost per month**	**$/month**	**$9.9**	**$39.0**	**$27.1**	**$105.5**

Table 16 Parameter values and scenario results for 2015

The lowest cost system, assuming all components can achieve the most optimistic assumptions about technical performance and cost, thus comprises a 90Ah battery and 370Wp PV, with an initial capital investment of just over $1000; however the battery would need replacing after ten years. This system could deliver the household cooking for twenty years at a cost of $10 a month. Standard PV panels are 0.8m x 1.6m and deliver 200Wp, so this systems would need 2 panels, or just over 2sqm.

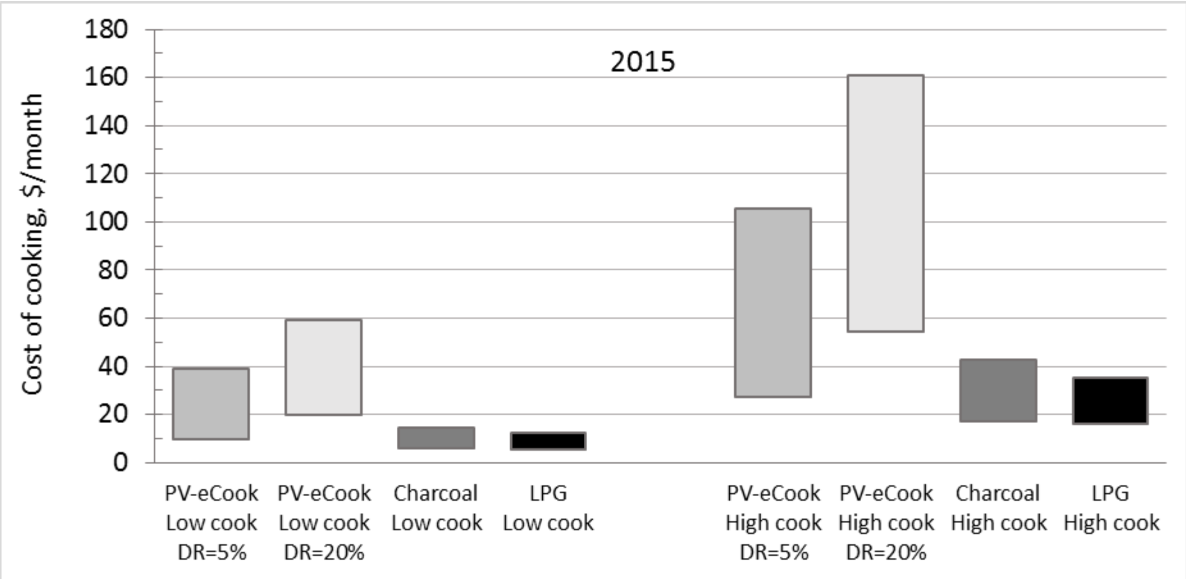
The most pessimistic assumptions would lead instead to a system requiring a 140Ah battery and a 460Wp PV: a 55% larger battery and a 25% larger PV. The initial investment cost is twice as large; however the total lifetime cost over 20 years is more than four times as large as the most optimistic system, as the battery lifetime is assumed to be only 5 years. This pushes the monthly cooking cost up by a factor of four.

If the daily cooking requirement is ‘high’ (i.e. three times that of the low case), the battery capacity increases to 260Ah and a 1kWp PV is needed, with the optimistic assumptions. Pessimistic assumptions lead to a 400Ah battery pack, a 1.3kWp PV and an initial investment of more than $6000: this implies a large PV array of some seven panels.

Figure 19 shows the results for these four scenarios, alongside similar ones for discount rate of 20%, and the outcomes for expenditure on conventional fuels to meet the same cooking requirements. Each bar represents the range of costs, arising due to the uncertainties in parameter values of (b): i.e. from more optimistic assumptions about efficiencies and prices to more pessimistic (thus the left hand bar shows the range of costs for the systems corresponding to the first pair of columns in Table 16). The different household cooking practices of (a) are characterised as ‘low cook’ and ‘high cook’ in the clusters to left and right respectively, and within each cluster for those, the performance of the different cooking types is compared. For electric cooking, the influence of the discount rate assumption is shown via bars for each of 5% and 20%.

Figure 19 Electric cooking costs, 2015

Note: PV-eCook denotes the PV-battery-electric cooking system



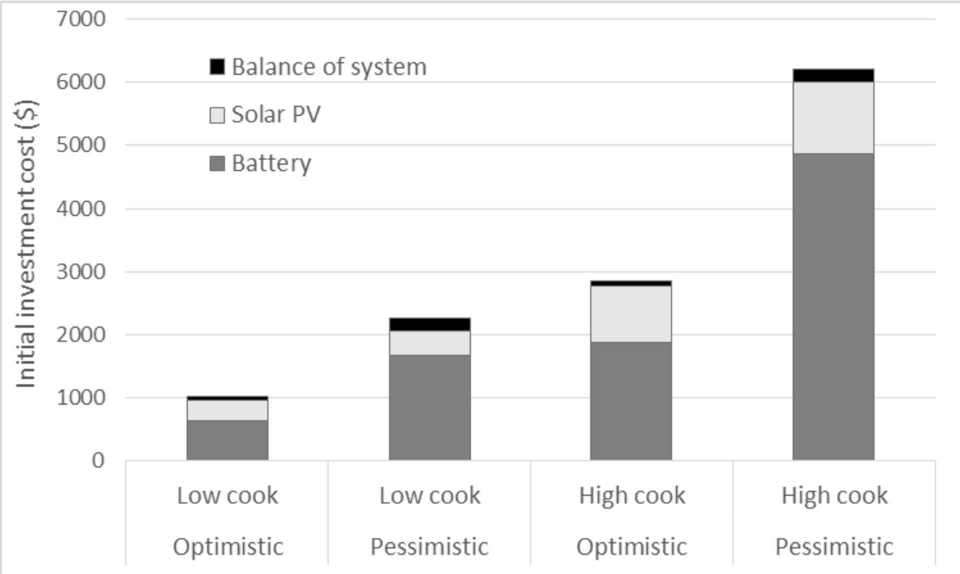
The range of uncertainty is clearly quite wide given the length of any one bar. This reflects the inclusion of the ranges for many different parameters. For 2015, a major part of the uncertainty is around the cost per kWh for the battery.

For the ‘low cook’ case, representing 1kWh of useful energy for cooking per day for a family, charcoal and LPG have very similar expenditure ranges, between $6 and $15 per month for charcoal and $6 and $13 for LPG, with the range simply reflecting geographic variation in prices. Financed at a 5% cost of capital, the electric cooker would cost between $10 and $40 a month, depending on a variety of assumptions about the achievable technical performance and cost of its components. Financed instead at 20%, the cost range risings to $20 to $60.

The ‘high cook’ case represents almost 3kWh of useful energy for cooking per day. Charcoal and LPG cooking expenditure increase proportionately, to ranges of $17 to $43 per month and $16 to $35 per month respectively. Costs for electric cooking do not increase by quite the same percentage, as not all system components must increase in proportion to the cooking use. However costs more than double, reflecting the need for a battery and PV system that is three times larger, to deliver three times the cooking energy each day. However as well as the absolute values increasing, the range of the uncertainty also increases. It is notable that for the high cooking case, there is significant overlap of the electric cooking cost range (assessed at 5% discount rate) with the expenditure for either charcoal or LPG, implying that in high fuel cost regions, a well-designed PV-battery cooker might offer a viable alternative even with the current state of technology development, if delivered via a government-financed programme.

Figure 20 illustrates the relative significance of the different components of the system to the initial investment cost: the importance of the batteries is evident. In this figure, 'Balance of System' includes the inverter, the charge controller, miscellaneous wiring and also the electric hob. The slightly greater significance of the balance of system in the two pessimistic cases reflects a relatively high degree of uncertainty over the appropriate values for these components. The figure shows only the initial purchase cost and doesn't take replacement costs into account. Adding replacement costs would make the significance of the balance of system slightly higher, as these components generally have shorter lifetimes than the battery, but the effect would be marginal.

Figure 20 Component contributions to total cost, 2015, DR=5%



Regarding the effect of the discount rate: this is a capital intensive cooking system, with very low operating costs, and thus the effect of discounting might have been expected to be small. However two factors have an influence. Firstly, discounting is applied both to costs, but also to the days on which cooking is delivered; this is the basis of the 'levelising' procedure, reflecting the fact that a consumer has a time preference, and would prefer to have a days-worth of cooking today than one in a year's time – just as they would for money, or for units of electricity. The higher discount rate reduces the value of cooking delivered in later periods, effectively requiring the investment to be recovered over a shorter time: thus the bars for DR=20% in Figure 19 are all shifted up compared to those for DR=5%. Secondly, some of the components require replacement during the 20 year accounting life of the system, and a higher DR will reduce the significance of such later investments. The scenarios with the most pessimistic technical assumptions (i.e. the upper end of each bar) include the greatest level of replacements, as component lifetimes are assumed to be shorter. Thus the cost increase between DR 5% and DR 20% for the upper end of each bar is relatively higher than the increase for the lower end of each bar, stretching the bars upwards.

5.2.2 Scenarios for 2020

Table 17 shows the assumptions and results for the same set of scenarios, but this time reflecting a view of the range of possibilities by 2020. In general, cost ranges have narrowed and costs have reduced; and some key technical parameters (notably for the battery) have improved. Note that to avoid over-optimism, we have not assumed technical improvements across the board: for example we assume no technical improvements in PV efficiency, but focus instead on expectations of continued cost reduction through learning effects.

2020, 5% Discount rate			**Scenario**	**5**	**6**	**7**	**8**
			Parameters	**Optimistic**	**Pessimistic**	**Optimistic**	**Pessimistic**
			Cooking	**Low cook**	**Low cook**	**High cook**	**High cook**
Component	**Parameter**	**Notes**	**Units**				
Cooking	$Euseful_{day}$	Useful energy into pan/food from hob	Wh/day	1020	1020	2960	2960
	Elcookday	Daily electricity use for cooking	Wh	1431	1431	4151	4151
	Lifecook	Lifetime of cooking appliance	Years	5	2	5	2
	Costhob	***Purchase cost of cooking appliance***	***$***	***10***	***15***	***10***	***15***
Inverter	Invertereffi	Inverter efficiency	%	97	90	97	90
	Losscable	Other cabling losses	%	5	15	5	15
	Lifeinverter	Lifetime of inverter	Years	10	5	10	5
	Costinverter	***Purchase cost of inverter***	***$***	***40***	***60***	***40***	***60***
Battery	$F_{mindepth}$	Battery minimum depth of charge	0-1	0.0	0.1	0.0	0.1
	Bvoltage	Battery voltage	V	24	24	24	24
	Beffi	Round trip efficiency	%	90	85	90	85
	$Lifebatt_{cal}$	Calendar lifetime of battery	Years	15	10	15	10
	$Lifebatt_{cyc}$	Cycle lifetime of battery	Cycles	6000	5000	6000	5000
	Lifebatt	Overall lifetime (min of cal. & cycle lives)	Years	15	10	15	10
	Bcap	Battery capacity	Ah	90	124	260	361
	BWh	Battery capacity	kWh	2.2	3.0	6.2	8.7
	Battprice	Battery price	$/kWh	200	300	200	300
	Costbatt	***Purchase cost of battery***	***$***	***430***	***896***	***1248***	***2600***
PV sizing	Epvday	Energy output from PV required	Wh	1721	2151	4993	6241
	$Peaksunhours_{min}$	Average daily peak sun hours	Hours	4.69	4.69	4.69	4.69
	Pvpowmin	Design peak power rating	W	367	459	1065	1331
	Pvprice	Purchase price of PV per Wp	$/Wp	0.62	0.62	0.62	0.62
	CostPVmin	***Purchase cost of PV panels***	***$***	***227***	***284***	***660***	***825***
Charge controller	Cccapmin	Charge controller capacity	A	15	19	44	55
	Lifecontrol	Lifetime of controller	Years	15	10	15	10
	Costcontrolmin	***Purchase cost of controller***	***$***	***10***	***50***	***10***	***50***
Overall costing	r	Discount rate		5	5	5	5
	Costinitial	Initial purchase cost of system	$	$718	$1,305	$1,968	$3,550
	Costsystemmin	Total cost of system (over 20yrs)	$	$1,228	$2,551	$3,297	$6,501
	$Ecookcostmin_{month}$	**Electric cooking cost per month**	**$/month**	**$6.5**	**$13.9**	**$17.5**	**$35.9**

Table 17 Parameter values and scenario results for 2020

For the optimistic cases, the battery and PV sizes are unchanged from 2015; however the battery has a longer life and a lower purchase price, and the PV price has reduced from 85c per Wp to 62c per Wp. More significant changes are seen in the pessimistic cases, where the batteries' minimum depth of charge is now 10% rather than 20% and the lifetime is assumed to have improved. Initial investment cost is now just over half of the level for 2015 and the lifetime cost is less than a third, as less frequent component replacement is needed. This for the low cook case the monthly cost of cooking has reduced to $14, and for the high cook case to $36.

Figure 21 shows the same sets of scenarios and fuel expenditures for the 2020 case, on the same axis scale as for 2015.

Charcoal and LPG expenditures see increases reflecting the range of assumptions about fuel price rises. As discussed for Table 17, the costs of the electric cooker fall, with the upper end of the cost range falling strongly through the assumptions of improved technical performance in batteries and from assumptions of reducing cost in all the major components. Individually these assumptions have been justified in section 3, based on the literature review. In combination the various assumptions lead to the cost ranges shown in the figure; failure to achieve any one of these assumed improvements would stretch the range bar upwards. However the analysis gives reasonable confidence that a system will be achievable that offers comparable costs to expenditures on conventional cooking fuels, and that could offer considerable savings in higher fuel cost regions or more widely if fuel cost increases are towards the upper end of the range modelled.

Figure 21 Electric cooking costs, 2020

Note: PV-eCook denotes the PV-battery-electric cooking system

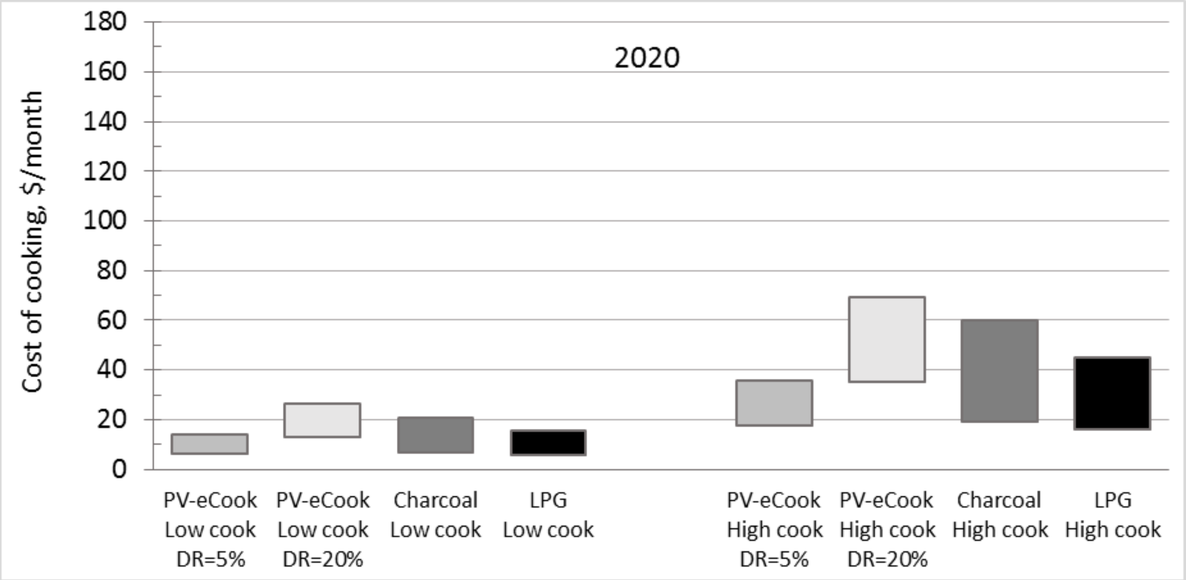
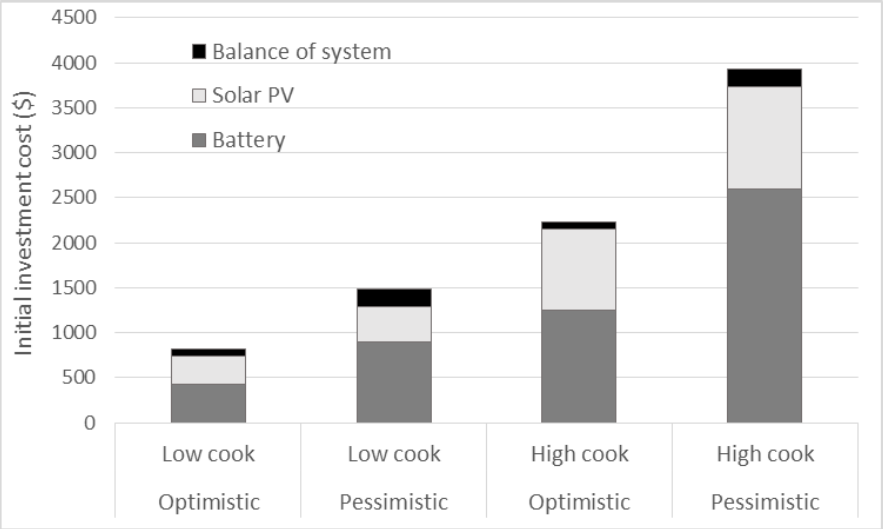


Figure 22 shows the component contributions to the investment cost. The significance of the batteries has reduced somewhat compared to the 2015 case, due to assumptions about technical and cost development for batteries in particular.

Figure 22 Component contributions to total cost, 2020, DR=5%



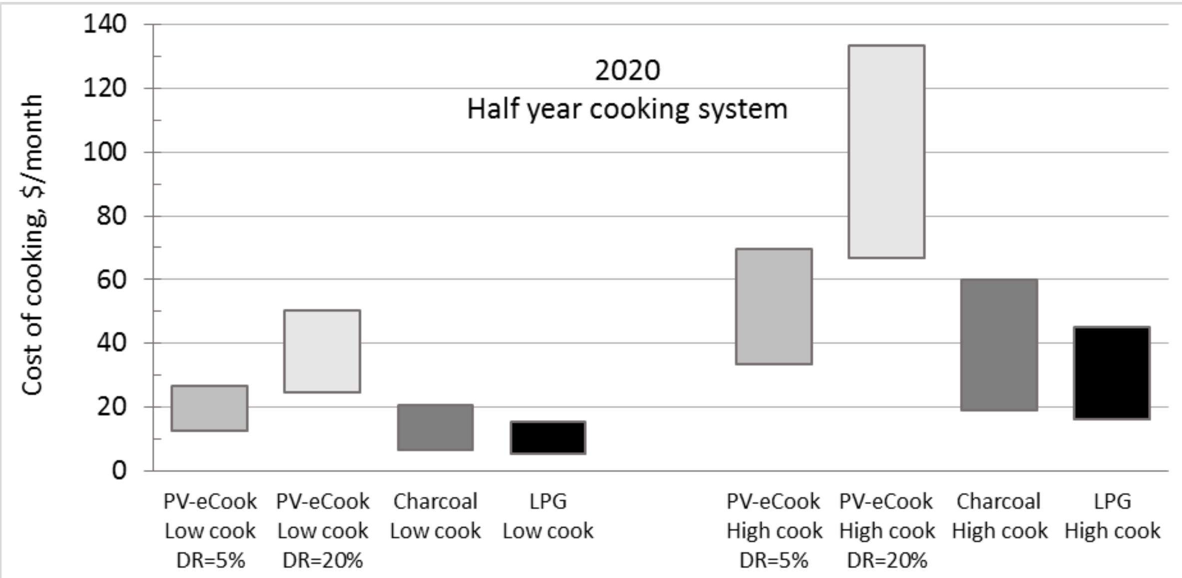
5.3 Additional sensitivities

5.3.1 Solar insolation

As discussed in 3.2.1.2, system design decisions, the PV-Battery system can be sized to operate well throughout the year, with a large enough PV array to charge the battery sufficiently even in the winter and/or monsoon periods when insolation levels are at their lowest. This will require a relatively large PV array, which is effectively larger than needed in sunnier parts of the year, but it will be able to deliver the 'cooking service' every day. An alternative choice is for a smaller PV that can deliver sufficient power for the system to operate only for a fraction of the year, when insolation levels are high. This is cheaper, but delivers cooking for only part of the year, with other fuels/stoves being used the rest of the time. The core analysis focused on a larger, whole-year design. The figure below shows the effect of designing the system to operate for only the sunniest half of the year, with the daily sun-hours increased by 20% to 5.7 hours.

Figure 23 Electric cooking costs, 2020, half year cooking system

Note: PV-eCook denotes the PV-battery-electric cooking system



The influence of moving to a smaller system sized to operate for only half of the year is striking, and perhaps counterintuitive, as the cost of delivering the cooking service increases. Whilst the capital cost of the smaller system is lower (by around 18%) due to the smaller PV, the costs are shared out over half of the cooking days. Thus cost per cooking-day or per meal is significantly higher. This suggests that adding a PV- battery cooker into a 'fuel stack' with households using it only occasionally will not be cost effective; the system needs to be the primary cooking device, substituting for the majority of purchased fuel. Note that the above costs for each cooking type represent just the costs per month for which cooking is undertaken with that cooker. Thus the full-year average cost per month for a household using the electric cooker for half the year would be half way between the values for the electric cooker and for the relevant conventional fuel cooker.

5.3.2 Other sensitivities

With the wide range of technical and cost parameters in the model, most of which have significant uncertainty, given that a system as envisaged here has not previously been developed, many other sensitivities could be explored. However from the scenarios already explored, it is evident that some key components and parameters dominate the overall system performance. The model is also linear, and thus in most cases, the influence of parameter change can be anticipated. Rather than present numerous additional figures, we present instead some general observations.

- Battery costs dominate the overall system cost, both for initial investment and replacement. Thus battery cost per kWh stored is a key parameter, as is technical lifetime, both for calendar and cycle degradation.
- The scenarios tested assume some ‘safety margins’ in sizing components to meet their duty cycle. However further such margins could be introduced: for example sizing the battery to store sufficient energy for more than one day’s cooking, to help the system ‘ride through’ the variability of solar output day to day. A 20% increase in battery capacity would flow through to increase overall system cost by around 15%, but would deliver a more reliable cooking experience.
- Similarly, the PV size could be increased, with battery capacity unchanged, as another measure to help overcome variability in insolation. The increase in PV size would have less impact on overall system cost, but a larger PV could in practice have a negative impact on siting and usability.
- The system design has been undertaken for the climatic conditions in sample sites in East Africa; these exhibited relatively low variability in the insolation received on average per day across the seasons. For the system to operate reliably throughout the year in a location with some periods of much lower insolation levels, the PV rise would need to increase in inverse proportion. A 20% increase in PV capacity leads to roughly 5% increase in monthly cooking cost.

SECTION 6

Discussion and conclusions

This study set out to explore the prospects for a solar-battery electric cooker for poor households, through comparing current and possible future costs compared to typical expenditures on conventional cooking fuels. A particular focus of the study was on the sensitivity of the results to a variety of parameters, given the novelty of the overall system proposition, continued cost reductions in solar PV, and that battery technology is advancing rapidly.

It is important to note that this is an initial study, intended to help scope out a larger research effort. As such, the aim was not to develop one single, optimal proposition; neither was the scope large enough to undertake comprehensive literature reviews and data gathering. The approach taken was to explore the key system components and to map out what might be sensible ranges on parameter estimates for those, and for how they might change over time with continued learning effects and technology development.

6.1 Validity of the overall concept

The results demonstrate that the core concept of a PV-battery-electric cooker as a substitute for purchased cooking fuels is a realistic one. Figure 21 illustrates that 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. The most positive case would be if an electric cooking system can be deployed in 2020 that meets the more optimistic assumptions in the study, and it is introduced in regions where traditional fuels are expensive. Furthermore, the analysis suggests that in such regions a system could compete even at the less optimistic end of the range of assumptions for performance and cost. With optimistic assumptions, the system could compete in a wider range of contexts.

The analysis has attempted to err on the side of caution, seeking not to adopt overly-optimistic assumptions that would make too strong a case for the new concept. However this suggests that there is some upside to the results: firstly, we assumed that replacement components do not benefit from ongoing technical improvements and cost reductions; logically there will be some benefit gained, acting to reduce overall costs slightly. Secondly, remembering the comment made in section 3.1.3.3, the calculations of charcoal cooking expenditure are likely to be on the low side, as efficiencies achieved in practice may well be lower than assumed.

The results section provided some sense of the nature of the system proposed and sized: from a 90Ah battery with 2 PV panels (plus associated charger controller, inverter and cabling) to something several times that size. A focus simply on monthly cooking cost and how that compares with traditional fuel expenditure does not give the complete picture: the larger systems proposed here might work technically and economically, but it is difficult to see them being accepted by poor households. Two PV panels should fit on most household roofs. Seven becomes a ‘PV roof’ of the sort requiring complex mounting systems. In addition, the larger the system, the larger the financial outlay, with implications for if, and how, such a system could be financed.

6.2 Financing and the energy services perspective

The approach taken for this initial study has been to assume the required investment, plus ongoing replacement costs, are financed by a third party, on some form of energy services model, with the user paying a monthly fee. The different discount rates trialled are intended to represent two distinct investor types. The 5% discount rate assumes investment is undertaken by a government agency or other large institution, which is not risk averse and can borrow cheaply. The 20% rate represents the perspective of a commercial institution seeking to make a reasonable return and with some risk sensitivity. 20% would be regarded as a very high rate for analysis of any commercial investment in the UK. However we recognise that even this rate will not reflect fully the perceived risks of a new capital intensive technology deployed in a developing country context, especially to poor households with no collateral. The report by Brown and Sumanik-Leary (2015) for Research Question 3 discusses this area a little, looking at experience with leasing high value products. However, the e-Cook concept needs to be seen not as simply a cooking appliance, seeking to compete on a commercial basis with the incumbents, as in this context a twenty year investment horizon may be unrealistic. Instead, the concept should arguably be treated as part of the investment in infrastructure needed to increase access to modern energy. In this light, a twenty year investment horizon is perfectly normal. Further exploration of this aspect is beyond the scope of the study.

6.3 Key components of the system

As anticipated, the battery is at the heart of the system, both in terms of the design process and in terms of cost. For this reason, we gave greatest attention to the characterisation of the battery and the values of its parameters. The analysis demonstrates that of particular significance are battery lifetime, achievable depth of discharge and unit cost. The prospects for all of these are bright, with continued development of the currently leading (Lithium-Ion) technologies alongside a wealth of innovation in materials, chemistry and systems engineering. The driver for these developments is not of course the prospect of off-grid applications in Africa; rather it is for deployment of electric (and hybrid electric) vehicles and for storage devices to go into grid-connected home energy systems in developed countries. The literature review sought to understand the state of the art and direction of developments in these markets, for which there has been considerable analysis of learning effects from the deployment to date, and future projections. However translating this experience into the present off-grid context, and to a smaller scale, is challenging, and gives rise to a considerable degree of uncertainty around the technical and cost parameters. The ranges included in the study are intended to reflect this, but more detailed design work and piloting will be essential to confirm the findings.

The solar PV is the second most significant component. This is much more certain technically than the batteries, but there is still considerable uncertainty over future costs. Again, we sought to assemble recent evidence on costs and insights into future reductions; however the quality of the data in the literature is low, with inconsistencies in the reporting of costs for different elements of the PV panel. The assumptions made for the study are intended to be on the conservative side, reflecting this uncertainty. Furthermore, for the study we made no assumption of continued technical improvement to PV, e.g. of increasing cell efficiency, or the use of concentrating technology at the cell level. Thus there may be some upside to the characterisation of PV in the study.

The minor components of the system - inverter, charge controller, miscellaneous wiring – were characterised in relatively simple terms, through required capacity, efficiency and cost. These components are in wide use in many markets globally and the assumption was made that appropriate units could be sourced or supplied to suit the cooking system developed, and sample data were used. A relatively wide range of parameter values were explored to reflect the uncertainty stemming from this simplistic treatment. As expected, the costs of these components is small in comparison to that of the battery and the PV and thus the assumptions have little influence. However for the 2020 cases, their significance increases as the cost of batteries is assumed to reduce.

6.4 The importance of time

The costs for the system in 2020 are lower, and the range of costs is narrower, reflecting assumptions about technical improvement, cost reduction and a general reduction in uncertainty. Given the evident influence of the battery costs in the whole system, and that the assumptions about improvements in batteries underpin much of the change from 2015 to 2020, a better understanding of the likely trends over time for batteries is important. As mentioned earlier, the drivers for battery development are from other application areas, and thus it will be challenging to determine a clear roadmap for off-grid battery systems.

In this analysis, time is also highly important with regards to the future developments in prices for conventional cooking fuels, notably charcoal and LPG. Forecasting fuel prices is a notoriously difficult activity, and in this case there are influences both from global fossil fuel markets and from the vagaries of local governance. It is possible that future fuel prices could move well outside the ranges proposed here, in either direction; however including larger ranges would go against historical trends, as well as rendering comparisons meaningless. It is also certain that over time there will be improvement in the stock of stoves in use across the developing world, with continued uptake of semi-improved and improved stoves, and refinement of designs towards increasing efficiency. Such further improvements will increase the competitiveness of conventional fuel cooking with the new PV-battery cooker: an example of the 'sailing ship effect' whence traditional ships improved as steam ships were developed. However the evidence for uptake of improved stoves suggests progress is slow, and with continued population growth, absolute numbers cooking with traditional fuels is expected to continue to increase. Trends for rural to urban migration also suggest more households will be established in places where collection of fuelwood is impossible, increasing the market for new forms of modern cooking.

2020 was adopted as a time horizon for this analysis for purely practical reasons: there is convincing published evidence of expected trends in technologies and their costs out to that period. However there is no suggestion that the trends will change markedly after 2020; for batteries in particular, it seems likely that there will be continued improvements to current technology types, and the emergence of new and improved chemistries, at least through the 2020s. Whilst we have not studied it directly, the competitiveness of e-Cook seems likely only to improve over time.

6.5 Final conclusion

The analysis undertaken for this study indicates that a PV-battery electric cooking system will be achievable in 2020 that offers comparable costs to expenditures on conventional cooking fuels. The system could offer considerable savings in higher fuel cost regions, or more widely if future fuel costs increase relatively strongly.

Notwithstanding this clear conclusion, the report has sought to highlight the uncertainties inherent to this concept. The opportunities for a well-designed system could be very large, but it will be essential to narrow the ranges of uncertainties if commercial and public sector interest is to be secured. The final section of the report indicates particular areas in which further research is warranted.

SECTION 7

Areas for further research

Areas of particular uncertainty, and components with key significance to the overall system performance and/or cost have been identified through the report. The list below is a brief synthesis of those points. In some cases the additional work required is to gather further material from the existing literature and evidence base, to take the analysis to a deeper level. In other cases we perceive a lack of data and suggest further primary research is needed.

Cooking patterns
The literature is relatively sparse on evidence about eating and cooking patterns, and how these translate into the energy requirements. Further work could be done on lab tests for appliance efficiencies, surveys and observations of practices and field testing of energy consumption in use.

Of particular importance is to improve the understanding of the daily variation in cooking practices. For the present study we assumed that the same meal type is cooked every day. In practice of course some days will see more cooking undertaken, either to feed more people, or to cook tougher meat or pulses requiring longer simmering.

Fuel prices
The fuel price evidence base is patchy, with different cost bases and hence uncertainty about inter comparison of data between regions. Much of the data are reported on a nominal cost basis, with nothing said about the inflation rates in those periods, thus rendering headline figures of rapid fuel price growth unhelpful. Furthermore, more careful attention is needed to how subsidy and other market distortions are handled in reported prices.

Market for PV-battery electric cooking
Extensive research has been undertaken under the auspices of improved cookstove programmes of the potential for shifting consumers onto improved stoves and modern fuels, through surveys of propensity to change as well as analysis of cooking expenditures, distinguishing between urban and rural areas, and different demographic groups. On the basis of the results of the present study, further work could now be done to estimate the size of the potential markets for the PV-battery cooker, albeit hampered by the above mentioned inconsistencies in fuel price data.

Solar PV
For the next stage in this work, effort should be made to gather evidence from the deployment of solar PV for other purposes, seeking to understand the costs of real systems, their performance in use, and to confirm lifetimes. In addition, the supply chain for PV in developing countries is evolving, and will be an important reference point for developing similar chains for an electric cooker. There is a range of experience for smaller systems (e.g. for solar lighting and solar home systems) as well as a growing body of experience with much larger systems. It is however likely that there will be limited evidence for PV units in the 0.4 to 1 kW range.

Regarding solar insolation: there are numerous resources available to help map insolation levels. It is uncertain if there is an existing tool that can map the average daily insolation according to month or season, as needed for system sizing. However it is certain that such data can be extracted from existing tools, and with some effort could be developed into national and regional maps, as part of a market assessment.

Batteries
Give the significance of batteries to this concept, further research into the technical design and into battery prospects is essential. In particular, attention should be given to translating existing data to be relevant for this size of stationary power system, and the developing country application.

The lifetimes, durability, cell and battery pack costs are of particular concern, as are the influence of high temperatures and of location in outdoor and potentially dusty locations.

Balance of system
As part of a more detailed system study, fuller analysis is needed of the operating cycles implied for controllers and inverter. A design study of the options for such components for a specific PV-battery-stove would be valuable.

Evidence should also be sought from field studies on the lifetimes and durability of the balance of system components, for example as part of solar home systems.

System design
For the next stage of this work, further detail will be needed on the system configuration, including wiring and control schemes.

Further consideration should also be given to the user experience in cooking, to feed into industrial design of the system: the size, location of components and general ergonomics.

Financing
A detailed study will be required of possible models of deployment, including past experience in other sectors (e.g. mobile communications, solar lanterns, solar home systems). However, given the significantly larger scale of the investment likely to be needed, further primary research is warranted, speaking to donors and commercial institutions about their appetite for the levels of risk involved. Similarly, whilst there is an existing body of evidence about householders' propensity to adopt new technology and to accept credit or other service models, further research focused on the type of system proposed here will be needed. As discussed in section 6.2 it seems most appropriate to regard e-Cook as infrastructure investment for access to modern energy. Further research is thus warranted into the grounds for this proposition, and then into the typical cost base for existing investment types, including grid extension and its distribution networks and micro- and nano-grid investments and concepts.

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Annex 1 Model Screenshot

			=Core range of values used in analysis			
			= wider sensitvity values			
			=calculated output			
			=data entry			Do not alte
						Note: to ru

Parameter	Description	Units	Parameter value (Reference values from literature) Optimistic	Central	Pessimistic	Scenario v
Electricity for cooking						
L_{peak}	Peak load = Max output of hob	W	500	1000	1000	1000
$Euseful_{day}$	Useful energy into pan/food from hob	Wh/day	1020	2000	2960	1020
EffiHob	Efficiency of hob, from electricity input to useful energy into pan/food	%	80	71.3	60	71.3
Elcookday	Daily electricity use for cooking (Wh) = $Euseful_{day}$ / ($Effi_{Hob}$ /100)	Wh	1275	2805	4933	1431
Cookdays	Number of days per year for electric cooking	Day/yr	365	365	200	365
Lifecook	Lifetime of cooking appliance	Years	10	5	2	5
Costhob	Purchase cost of cooking appliance	$	10	15	20	10
Inverter						
Inverterrating	Minimum rating for Inverter rating = L_{peak}	W	500	1000	1000	1000
Invertereffi	Inverter efficiency	%	97	95	90	97
Losscable	Other cabling losses	%	5	10	15	5
Lifeinverter	Lifetime of inverter	Years	20	10	5	10
Costinverter	Purchase cost of inverter; related to Inverterrating	$	40	60	80	40
Battery						
F_{store}	Battery number of days storage factor	>=1	1	1.5	3	1.0
$F_{mindepth}$	Battery minimum depth of charge factor	0-1	0	0.1	0.2	0.0
Bvoltage	Battery voltage	V	24	24	24	24.0
Beffi	Round trip efficiency	%	90	85	80	90.0
$Lifebatt_{cal}$	Calendar lifetime of battery	Years	15	10	5	10.0
Bcapaddcal	Additional battery capacity for calendar decay	%	10	10	10	10.0
$Lifebatt_{cyc}$	Cycle lifetime of battery	Cycles	6000	5000	3000	6000.0
Bcapaddcyc	Additional battery capacity for cycle decay	%	15	15	15	15.0
Bcap	Battery capacity = (ELcookday * Fstore * (1/(Invertereffi/100)) * (1+Losscable/100)) *	Ah	80	332	1539	90
BWh	Battery capacity = Bcap * Bvoltage / 1000	kWh	1.9	8.0	36.9	2.2
Battprice	Battery price	$/kWh	200	300	500	300
Lifebatt	Overall lifetime of battery, min of calendar and cycle lives	Years	15	10	5	10
Costbatt	Purchase cost of battery = BWh * Battprice	$	383	2388	18468	645
PV sizing						
Fpvcap	Margin of PV capacity over daily electricity demand factor	>=1	1	1.2	1.5	1
Epvday	Energy output from PV required = Bcap * (1-$F_{mindepth}$) /(1+(Bcapaddcyc+bcapaddcal)/100	Wh	1534	6878	35458	1721
$Peaksunhours_{min}$	Average daily peak sun hours in the least sunny month	Hours	4.69	4.69	4.69	4.69
$Peaksunhours_{avg}$	Average daily peak sun hours for best six month	Hours	5.63	5.63	5.63	5.63
Pvpowmin	Design peak power rating, sized to min sun periods = Epv_{day} / Peaksunhoursmin	W	327	1467	7560	367
Pvpowavg	Design peak power rating, sized to best sun periods = Epv_{day} / Peaksunhoursavg	W	272	1222	6300	306
Pvprice	Purchase price of PV per peakwatt	$/Wp	0.62	0.75	0.85	0.85
LifePV	Lifetime of PV	Years	25	20	10	20
CostPVmin	Purchase cost of PV panels, sized to min sun periods = PVpowmin * PVprice	$	203	1100	6426	312
CostPVavg	Purchase cost of PV panels, sized to best sun periods = PVpowavg * PVprice	$	169	917	5355	260
Charge controller						
Cccapmin	Charge controller capacity, PV sized to min sun periods = PVpowmin / Bvoltage	A	14	61	315	15
Cccapavg	Charge controller capacity, PV sized to best sun periods = PVpowavg / Bvoltage	A	11	51	263	13
Lifecontrol	Lifetime of controller	Years	20	15	5	15
Costcontrolmin	Purchase cost of controller, PV sized to min sun periods; related to Ccap	$	10	25	100	25
Costcontrolavg	Purchase cost of controller, PV sized to best sun periods; related to Ccap	$	10	25	100	25
Overall costing						
r	Discount rate		5	10	20	5
Costsystemmin	Total capital cost of system, sized to min sun periods, including replacements for 20 year	$				$1,772
Costsystemavg	Total capital cost of system, sized to best sun periods, including replacements for 20 year	$				$1,695
NPVsystemmin	Net Present value of system, sized to min sun periods	$				$1,484
NPVsystemavg	Net Present value of system, sized to best sun periods	$				$1,419
$Ecookcostmin_{day}$	Electric cooking cost per day, sized to min sun periods	$/day				$0.33
$Ecookcostavg_{day}$	Electric cooking cost per day, sized to best sun periods	$/day				$0.62
$Ecookcostmin_{month}$	Electric cooking cost per month, sized to min sun periods	$/month				$9.9
$Ecookcostavg_{month}$	Electric cooking cost per month, sized to best sun periods	$/month				$19.0
Checks						
$C\text{-}rate_{discharge}$	Ratio of the rate of discharge to battery capacity = (L_{peak} / Bvoltage)/ Bcap (Max 1C)	A	0.26	0.13	0.03	
$C\text{-}rate_{charge}$	Ratio of the rate of charge to battery capacity = PVcurr / Bcap (Max 0.8C)	A	0.14	0.15	0.17	

Annex 2 Scenario parameters and results

Parameter	Description	Units	Scenario																
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
			Core, 5%DR	Core, 5%DR	Core, 5%DR	Core, 5%DR	Core, 5%DR	Core, 5%DR	Core, 5%DR	Core, 5%DR	Core, 20%DR	Core, 20%DR	Core, 20%DR	Core, 20%DR	Core, 20%DR	Core, 20%DR	Core, 20%DR	Core, 20%DR	Core, 5%DR
			2015 +ve low cook	2015 -ve low cook	2015 +ve high cook	2015 -ve high cook	2020 +ve low cook	2020 -ve low cook	2020 +ve high cook	2020 -ve high cook	2015 +ve low cook	2015 -ve low cook	2015 +ve high cook	2015 -ve high cook	2020 +ve low cook	2020 -ve low cook	2020 +ve high cook	2020 -ve high cook	2020 +ve low cook Effi cook
Electricity for cooking																			
L_{peak}	Peak load = Max output of hob	W	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
$Euseful_{day}$	Useful energy into pan/food from hob	Wh/day	1020	1020	2960	2960	1020	1020	2960	2960	1020	1020	2960	2960	1020	1020	2960	2960	1020
EffiHob	Efficiency of hob, from electricity input to useful energy into pan/food	%	71.3	71.3	71.3	71.3	71.3	71.3	71.3	71.3	71.3	71.3	71.3	71.3	71.3	71.3	71.3	71.3	80
Elcookday	Daily electricity use for cooking (Wh) = $Euseful_{day}$ / ($Effi_{Hob}$ /100)	Wh	1431	1431	4151	4151	1431	1431	4151	4151	1431	1431	4151	4151	1431	1431	4151	4151	1275
Cookdays	Number of days per year for electric cooking	Day/yr	365	365	365	365	365	365	365	365	365	365	365	365	365	365	365	365	365
Lifecook	Lifetime of cooking appliance	Years	5	2	5	2	5	2	5	2	5	2	5	2	5	2	5	2	5
Costhob	Purchase cost of cooking appliance	$	10	15	10	15	10	15	10	15	10	15	10	15	10	15	10	15	10
Inverter																			
Inverterrating	Minimum rating for Inverter rating = L_{peak}	W	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Invertereffi	Inverter efficiency	%	97	90	97	90	97	90	97	90	97	90	97	90	97	90	97	90	97
Losscable	Other cabling losses	%	5	15	5	15	5	15	5	15	5	15	5	15	5	15	5	15	5
Lifeinverter	Lifetime of inverter	Years	10	5	10	5	10	5	10	5	10	5	10	5	10	5	10	5	10
Costinverter	Purchase cost of inverter; related to Inverterrating	$	40	80	40	80	40	60	40	60	40	80	40	80	40	60	40	60	40
Battery																			
F_{store}	Battery number of days storage factor	>=1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$F_{mindepth}$	Battery minimum depth of charge factor	0-1	0.0	0.2	0.0	0.2	0.0	0.1	0.0	0.1	0.0	0.2	0.0	0.2	0.0	0.1	0.0	0.1	0.0
Bvoltage	Battery voltage	V	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
Beffi	Round trip efficiency	%	90.0	85.0	90.0	85.0	90.0	85.0	90.0	85.0	90.0	85.0	90.0	85.0	90.0	85.0	90.0	85.0	90.0
$Lifebatt_{cal}$	Calendar lifetime of battery	Years	10.0	5.0	10.0	5.0	15.0	10.0	15.0	10.0	10.0	5.0	10.0	5.0	15.0	10.0	15.0	10.0	15.0
Bcapaddcal	Additional battery capacity for calendar decay	%	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
$Lifebatt_{cyc}$	Cycle lifetime of battery	Cycles	6000.0	3000.0	6000.0	3000.0	6000.0	5000.0	6000.0	5000.0	6000.0	3000.0	6000.0	3000.0	6000.0	5000.0	6000.0	5000.0	6000.0
Bcapaddcyc	Additional battery capacity for cycle decay	%	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
Bcap	Battery capacity = (ELcookday * Fstore * (1/(Invertereffi/100)) * (1+Losscable/100)) *	Ah	90	140	260	406	90	124	260	361	90	140	260	406	90	124	260	361	80
BWh	Battery capacity = Bcap * Bvoltage / 1000	kWh	2.2	3.4	6.2	9.8	2.2	3.0	6.2	8.7	2.2	3.4	6.2	9.8	2.2	3.0	6.2	8.7	1.9
Battprice	Battery price	$/kWh	300	500	300	500	200	300	200	300	300	500	300	500	200	300	200	300	200
Lifebatt	Overall lifetime of battery, min of calendar and cycle lives	Years	10	5	10	5	15	10	15	10	10	5	10	5	15	10	15	10	15
Costbatt	Purchase cost of battery = BWh * Battprice	$	645	1680	1872	4876	430	896	1248	2600	645	1680	1872	4876	430	896	1248	2600	383
PV sizing																			
Fpvcap	Margin of PV capacity over daily electricity demand factor	>=1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Epvday	Energy output from PV required = Bcap * (1-$F_{mindepth}$) /(1+(Bcapaddcyc+bcapaddcal)/100)	Wh	1721	2151	4993	6241	1721	2151	4993	6241	1721	2151	4993	6241	1721	2151	4993	6241	1534
$Peaksunhours_{min}$	Average daily peak sun hours in the least sunny month	Hours	4.69	4.69	4.69	4.69	4.69	4.69	4.69	4.69	4.69	4.69	4.69	4.69	4.69	4.69	4.69	4.69	4.69
$Peaksunhours_{avg}$	Average daily peak sun hours for best six month	Hours	5.63	5.63	5.63	5.63	5.63	5.63	5.63	5.63	5.63	5.63	5.63	5.63	5.63	5.63	5.63	5.63	5.63
Pvpowmin	Design peak power rating, sized to min sun periods = Epv_{day} / Peaksunhoursmin	W	367	459	1065	1331	367	459	1065	1331	367	459	1065	1331	367	459	1065	1331	327
Pvpowavg	Design peak power rating, sized to best sun periods = Epv_{day} / Peaksunhoursavg	W	306	382	887	1108	306	382	887	1108	306	382	887	1108	306	382	887	1108	272
Pvprice	Purchase price of PV per peakwatt	$/Wp	0.85	0.85	0.85	0.85	0.62	0.62	0.62	0.62	0.85	0.85	0.85	0.85	0.62	0.62	0.62	0.62	0.62
LifePV	Lifetime of PV	Years	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
CostPVmin	Purchase cost of PV panels, sized to min sun periods = PVpowmin * PVprice	$	312	390	905	1131	227	284	660	825	312	390	905	1131	227	284	660	825	203
CostPVavg	Purchase cost of PV panels, sized to best sun periods = PVpowavg * PVprice	$	260	325	754	942	189	237	550	687	260	325	754	942	189	237	550	687	169
Charge controller																			
Cccapmin	Charge controller capacity, PV sized to min sun periods = PVpowmin / Bvoltage	A	15	19	44	55	15	19	44	55	15	19	44	55	15	19	44	55	14
Cccapavg	Charge controller capacity, PV sized to best sun periods = PVpowavg / Bvoltage	A	13	16	37	46	13	16	37	46	13	16	37	46	13	16	37	46	11
Lifecontrol	Lifetime of controller	Years	15	5	15	5	15	10	15	10	15	5	15	5	15	10	15	10	15
Costcontrolmin	Purchase cost of controller, PV sized to min sun periods; related to Ccap	$	25	100	25	100	10	50	10	50	25	100	25	100	10	50	10	50	10
Costcontrolavg	Purchase cost of controller, PV sized to best sun periods; related to Ccap	$	25	100	25	100	10	50	10	50	25	100	25	100	10	50	10	50	10
Overall costing																			
r	Discount rate		5	5	5	5	5	5	5	5	20	20	20	20	20	20	20	20	5
Costsystemmin	Total capital cost of system, sized to min sun periods, including replacements for 20 year	$	$1,772	$7,965	$4,820	$21,488	$1,228	$2,551	$3,297	$6,501	$1,772	$7,965	$4,820	$21,488	$1,228	$2,551	$3,297	$6,501	$1,109
Costsystemavg	Total capital cost of system, sized to best sun periods, including replacements for 20 year	$	$1,695	$7,600	$4,644	$21,000	$1,190	$2,454	$3,186	$6,313	$1,695	$7,600	$4,644	$21,000	$1,190	$2,454	$3,186	$6,313	$1,076
NPVsystemmin	Net Present value of system, sized to min sun periods	$	$1,484	$5,838	$4,057	$15,778	$973	$2,078	$2,617	$5,369	$1,151	$3,466	$3,169	$9,410	$759	$1,528	$2,063	$4,048	$879
NPVsystemavg	Net Present value of system, sized to best sun periods	$	$1,419	$5,585	$3,894	$15,401	$936	$2,000	$2,508	$5,201	$1,097	$3,338	$3,016	$9,159	$722	$1,473	$1,954	$3,902	$846
$Ecookcostmin_{day}$	Electric cooking cost per day, sized to min sun periods	$/day	$0.33	$1.28	$0.89	$3.47	$0.21	$0.46	$0.58	$1.18	$0.65	$1.95	$1.78	$5.29	$0.43	$0.86	$1.16	$2.28	$0.19
$Ecookcostavg_{day}$	Electric cooking cost per day, sized to best sun periods	$/day	$0.62	$2.46	$1.71	$6.77	$0.41	$0.88	$1.10	$2.29	$1.23	$3.76	$3.39	$10.31	$0.81	$1.66	$2.20	$4.39	$0.37
$Ecookcostmin_{month}$	Electric cooking cost per month, sized to min sun periods	$/month	$9.9	$39.0	$27.1	$105.5	$6.5	$13.9	$17.5	$35.9	$19.7	$59.3	$54.2	$161.0	$13.0	$26.2	$35.3	$69.3	$5.9
$Ecookcostavg_{month}$	Electric cooking cost per month, sized to best sun periods	$/month	$19.0	$74.7	$52.1	$206.0	$12.5	$26.7	$33.5	$69.6	$37.5	$114.2	$103.2	$313.5	$24.7	$50.4	$66.9	$133.6	$11.3

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