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Affordability for sustainable energy development products

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HIGHLIGHTS

- Clean cookstoves that also generate electricity improve affordability.
- Excel spreadsheet model to assist stakeholders to choose optimum technology.
- Presents views for each stakeholder villager, village and country.
- By adding certain capital costs, affordability and sustainability are improved.
- Affordability is highly dependent on carbon credits and social understandings.

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ABSTRACT

Clean burning products, for example cooking stoves, can reduce household air pollution (HAP), which prematurely kills 3.5 million people each year. By careful selection of components into a product package with micro-finance used for the capital payment, barriers to large-scale uptake of products that remove HAP are reduced. Such products reduce smoke from cooking and the lighting from electricity produced, eliminates smoke from kerosene lamps. A bottom-up financial model, that is cognisant of end user social needs, has been developed to compare different products for use in rural areas of developing countries. The model is freely available for use by researchers and has the ability to assist in the analysis of changing assumptions. Business views of an individual villager, the village itself and a country view are presented. The model shows that affordability (defined as the effect on household expenses as a result of a product purchase) and recognition of end-user social needs are as important as product cost. The effects of large-scale deployment (greater that 10 million per year) are described together with level of subsidy required by the poorest people. With the assumptions given, the model shows that pico-hydro is the most cost effective, but not generally available, one thermo-acoustic technology option does not require subsidy, but it is only at technology readiness level 2 (NASA definition) therefore costs are predicted and very large investment in manufacturing capability is needed to meet the cost target. Thermo-electric is currently the only technology that can be used worldwide every day of the year and is available without research. However, it is not yet self-financing and therefore requires subsidy or diversion of more household income to be affordable. A combination of photovoltaic and clean cookstove may be suitable in areas where sufficient solar radiation is available on most days. Affordability is shown to be highly dependent on the income that can be derived from carbon credits.

1. Introduction

In rural areas of developing countries, there are two main problems; 3 billion people suffer smoke inhalation with the associated ill health and 1.6 billion do not have access to electricity. In most rural areas there is an overall economic (as well as health) benefit to reducing smoke through the use of improved cookstoves [1]. Interestingly, although most recent effort for reducing smoke inhalation has concentrated on smoke produced from wood [2], there are also benefits of electric lighting on health by reducing smoke from kerosene lamps used for lighting [3]. Although off-grid electrically generating technologies are available in remote rural areas of Nepal, penetration of mains electricity to rural areas is only 1% of total energy consumption [4].

An analysis of off-grid renewable energy systems based on a literature review covering Bangladesh and Fiji [5] shows that key requirements for success require cognisance of the social, institutional, economic and policy aspects of implementation. This view is supported by work done in India [6] where small-scale power

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generation systems based on the renewable energy sources are more efficient and cost-effective than providing mains supplies, particularly to remote communities. Early work on providing sustainable energy for development concentrated on providing the lowest cost solution [7]. Other work has shown that the social context is highly influential to large-scale sustainable energy uptake [8]. A study on Renewable Energy (RE) policy [9] shows that awareness levels in adopting RE-technologies and willingness of people to access and pay for electricity have increased significantly. However, there is a huge financial gap between the cost of electrification and the affordability. Bridging this gap is a crucial issue that needs to be addressed for the smooth expansion of rural electrification in the country.

The term "affordability" is used in different ways. There are a number of empirical studies on energy access and affordability, drawing lessons based on the experience of three developing countries—Brazil, Bangladesh, and South Africa, and [10] cites the Energy Sector Management Assistance Programme, 2003; "Affordability is a politicized concept". Many researchers take a statistical view of affordability, particularly when discussing UK energy systems [11]. This top-down approach is suitable for analysing energy systems in affluent areas, where there are multifaceted spending choices and mature energy generation and distribution systems in place. In the case of the low-income rural households, a bottom-up approach to the analysis is required as no energy infrastructure is in place and lack of income is the major constraint.

To remove any bias due to politics and make the results more applicable to people at the Bottom of the Pyramid (BoP), this paper defines affordability in a different and very specific mathematical way: when a technology intervention is made, it is considered affordable when the net change in income – expenditure is greater or equal to zero. The term is then applied at the householder, village or country level. Where income is less than expenditure, the amount of subsidy needed for implementation is a measure of the relative affordability between technological interventions.

Little bottom-up work has been done on comparing the economics across different stakeholders of different methods of delivering off-grid rural electricity in combination with clean cookstoves, or in how to package products together to improve affordability. This paper presents a model to compare an energy product from three views: the villager in a rural area, the local shopkeeper, and the region or country with the goal to provide both sustainable electricity and clean cooking stoves, thus improving health by removing the two main smoke problems. By providing a business case at all these three levels, many social barriers to large-scale deployment are removed.

Affordability alone is not sufficient to make an impact on the global scale; any solution also needs to be sustainable. Sustainability has three facets: it should be built from sustainable materials, use renewable fuel and be accepted by all the stakeholders. Only the latter two are within the scope of this paper.

Indoor household air pollution (HAP) is thought to prematurely kill 3.5 million people each year [12]. Recent, as yet unpublished research indicates that removing the smoke from cooking is not sufficient to improve health in all cases. Kerosene lamps used for lighting also produces significant smoke [13] and people often revert to smokier stoves for a variety of reasons [14].

Thus, the motivation behind this paper is to provide a means via an MS Excel™ spreadsheet model to compare a set of technological interventions that have the potential to improve health due to HAP and in so doing, assisting decision makers and implementers to choose affordable, sustainable and holistic solutions. The model can be used to predict outcomes for households at different income levels. This paper presents data for those at the BoP only; people earning £2 or less per day.

2. Methodology

The need for clean cooking stoves has been around for 50 years and yet outside China coverage is only 8%. Additionally, rural electrification is among the priority areas of government policies, particularly in Nepal. The methodology of this paper is to produce a mathematical model in MS Excel™ that shows the financial benefits of combining a clean cooking stove with electrical generation. In doing so, the total benefits are greater than the sum of the parts. We chose a number of technologies for the model, some that provided clean cooking and electrical generation in one unit such as thermo-acoustic and thermo-electric and others such as hydro and photovoltaic that required combination with a clean cookstove to meet the combined smoke free and electrical generating requirement. Previous research has shown that socio-technical interactions can make a significant difference to householder finances and so the model also includes additional functions such as mobile phone charging and both indoor and torch lighting systems. The latter is essential to remove the need for kerosene lighting; without torches, kerosene is used as mobile lighting to tend animals, go to the toilet etc. at night.

The hypothesis is that adding additional product functionality and hence cost to the solution reduces the net financial burden on the householder, village and country, thus improving the affordability of the intervention as a whole. Products such as photovoltaic are mature technology and easily available, whereas thermo-acoustic technology is in its infancy as far as large-scale production is concerned. In order to compare products at such a divergent technology release levels, the model breaks down the solution into a number of functional elements and uses simple rules for each element. If a function is common to more than one solution, for example the cooking hob itself, only one cost for that function is used across all solutions. For products at an early technology release level, the predicted cost in volume using a method previously developed by the author [8] is used.

To test the hypothesis seven examples of technologies, are used to meet the overall goal stated earlier. In two cases, a combination of technologies forms the overall solution. The model clearly defines the assumptions used, which are described in detail below. For testing specific cases, or as commodity prices alter over time, the assumptions can be changed to see the effects at each level from householder to country.

3. Affordability versus cost

This paragraph outlines how correct application of additional cost can significantly improve affordability of the product. However, any extra cost has to take cognisance of the social context so that the cost is targeted to improve affordability. By concentrating on affordability in addition to product cost, packaged solutions emerge that increase uptake, remove barriers to implementation and so improve acceptability of the product.

3.1. Social context: villager

Trials in Nepal and Kenya [15], and other areas [16] installed Photovoltaic panels and clean cookstoves in village households, the electricity was mainly used for lighting, radio and charging mobile phones. The lighting provided was static and internal to the dwelling. Part of the early business case for the installation was that the lighting provided would mean that kerosene use would fall to almost zero. (Kerosene lamps are used for lighting in many villages and consume the vast majority of kerosene purchased.) Follow-up studies revealed that kerosene use had only dropped by 25%; this considerably and negatively affected the business case, as the reduction in kerosene payments was a major financial element. The follow-up showed that the kerosene lamps were used outside for tending animals and to go to the toilet. The static lights supplied did not provide outside lighting so kerosene lamps had to be used. The work emphasized the need for both understanding the social element of any new technology and feedback of end-user use. In order to realise fully the benefit of reduction in kerosene use, additional cost was added, in the form of re-chargeable torches for use outside. This small increase in cost was more than compensated by the reduction to almost zero of kerosene use.

3.2. Carbon credits

Carbon trading has the potential to generate income for people who use sustainable fuel, both in cooking and generating electricity. However, there are strict rules on verification; proving compliance in areas of high illiteracy or where corruption is endemic creates verification difficulties. Solving this issue means extra income for householders thus adding to affordability, providing the extra cost in verification is not too high.

3.3. Decrease workload, increase income

A product that saves effort means that the time saved can be used to generate income. The model variable "village income rate" (set at £2 per day) is the income per household averaged over the village. It is used to compute the extra income from time saved in efficiency improvements for example collecting wood, due to the better efficiency of the stoves requiring less fuel. The extra income is likely to be higher than this figure as mobile phone use improves the efficiency of agriculture; mobile phone use is now estimated to be in excess of 50% in the rural areas. Work in Uganda [17] has shown that there is scope for additional income generation from similar efficiency improvements.

4. Stakeholders

In large undertakings, vested interests can become a barrier to successful implementation and hence make solutions unsustainable. This section considers the key stakeholders and gives some examples of how barriers can be removed.

4.1. Social context: shop keeper

The change in purchasing behaviour by the householder may have an indirect effect on the shopkeeper by affecting business finance and hence the shopkeeper's affordability. In areas of low income, there is little scope to sell more goods to compensate for the reduction in kerosene use. Therefore, any sustainable energy products should involve increasing the shopkeeper's income to compensate. Possible solutions are for products to be hired, with the shopkeeper collecting hire purchase payments, or to be involved in the capital purchase or maintenance. This paper uses the term shopkeeper as a summary term for local stakeholders that may be affected by product changes.

4.2. Regional or country governance

The benefits of improving wealth and health of the regions, will in principle be well received by the government providing such improvements do not bring negative elements. The two main inhibitors here are balance of payments and export of finance i.e. affordability at the country level. Purchase of products from outside the country would result in a worsening of country balance of payments, unless compensated in some way. Use of local labour in product manufacture and of course reduction in oil imports help to balance this.

The products require capital investment. This funding can come from banks, cooperatives, charitable donations, or industrial corporations. Profit is a major motivator to product deployment and at the local level is positive. However, one must ensure that net cash flow from such funding ventures is zero, or forms an income stream to the country. The model aggregates the household effects on income and expenditure over a countrywide area to assist governments in comparing different technological solutions, and to help negotiate the cost of imports or required subsidies.

5. Affordability model

5.1. Material and methods

The scenario identified earlier highlights the complication of large-scale deployment of sustainable energy products. Small changes in product design that affect the social acceptability, or selling the wrong product mix in the wrong way make a significant difference to the affordability and hence the uptake. An affordability model has been produced (downloadable from [18]) that allows key decisions to be made. The assumptions used are transparent and can easily be changed; then the effect at each stakeholder level can be ascertained. The version of the model presented here includes a variety of product solutions. The calculation section explains the assumptions used.

A simple business model is assumed whereby financial institutions pay capital cost, through for example micro-finance with the associated interest and capital payback through a hire purchase type of arrangement. In the tables below, the packaged price is for a solution that generates electricity and is smoke free. The cost of the clean cookstove is added to the PV and pico-hydro solution and so do not appear separately. Suitable sites for pico-hydro are not universally available, so the assumptions have a country coverage figure. This is the percentage of the country that could be supplied by pico-hydro.

The results below are presented in £GB. The model is able to convert to other currencies and the notes page in the spreadsheet explains how this can be done.

5.2. Products modelled

The model includes the products that require packaging as described.

1. Photovoltaic and clean cookstove
2. Pico-hydro and clean cook stove [19].
3. Thermo-electric [20].
4. Thermo-acoustic TRL 4 [21].
5. Thermo-acoustic TRL 3.
6. Thermo-acoustic TRL 2.

5.3. Like- for-like cost comparisons

The product sheet contains costs for each geometric feature of the product. Where features are common, for example all the stoves require a cooking hob, the costs are read across. In this way even if the absolute costs change, the relative costs are preserved, so a like-for-like comparison is valid. The concept of Technology Readiness Level (TRL) [22] is used.

6. Description of calculations used in the model

The variable "village income rate" is the £2 per day described earlier. The model assumes that people involved in sales and product maintenance earn a premium on this figure and is stored in the "village wage rate (maintenance)" variable with the cost of training stored in "average cost of training per person"..

6.1. Cost calculations

Comparing costs between products at different stages of development is problematic; one cannot compare the direct manufacturing cost of an early rig with a volume-manufactured product. The model assumes that all finance is available through micro-finance or a similar borrowing mechanism with capital and interest payments. The pricing approach taken in this paper is to use the selling price of a product manufactured in volume. Where a product is already available, the published price is used; when in development, the target cost estimate of manufacture plus typical profit and overhead margins are used. When comparing features, the costs of each feature are used where available, or are estimated on a like-for-like basis with solutions where the feature cost is known. As the model assumes no change to cooking habits, the actual energy used will vary depending on whether the electricity is used at the same time as generation or later, having been stored. The cost of a small battery is included, but the charging inefficiency is excluded, to simplify comparisons.

Output electrical power has been normalised to 50 W of generation over 3 hours per day to get a fair comparison between products. The normalisation is different for each technology and is described below.

The electrical products all require casings, invertors and battery charging electronics; these are included under the heading balance of plant and assumed the same cost for all these products. Where features are common across multiple products (such as heat exchangers and cooking hobs) the same cost is used.

6.1.1. Common features

Commodity prices being highly volatile are taken from spot prices at some point during the writing of this paper: Oil $100 per barrel, 159 l per barrel. Kerosene carbon emissions are 90% of oil value = 2.7 kg per litre. Retail price of kerosene £1 per litre. Interest on micro-finance loans = 15%. Ref. [16] provided the amount of kerosene typically used per month and current wood use. Likely fuel consumption savings of a more efficient cooking stove is taken as 50% better than the 3-stone stove (i.e. it uses half the wood) being a reasonable average of products on the market.

Product life is an average value from data sheets where available, or product design requirements for products at an early TRL. Battery = 3 years, Thermo electric and acoustic = 10 years, pico-hydro = 20 years. Maintenance is taken as 10% of the capital cost per year.

Carbon credits are a potential income for poor rural families; however verification can be problematic [23] and to obtain the best price, world standards should be adopted [24]. This paper assumes that obstacles can be overcome and will be the topic of future documentation. This Ref. [25] states that (for micro-hydro) 2000 kW h of electricity prevents 1 tonne of CO_2 emissions and is the conversion factor used. At January 2013 the price of carbon trading was around €6 per tonne of CO_2. A Bloomberg release [26] has indicated that this is an anomaly and is predicting a price of £55 to £83 (€60 to €90) by 2020. This paper assumes a lower rate of £55 per tonne giving an income of £0.10 per kW h of electricity produced. No account has been taken of the benefits of thermal energy, as the target market is people who already currently cook on an open fire.

People per household is set to 4 people, being a reasonable average for developing countries.

Income generated. The "village income rate" is used to calculated income based on time saved collecting wood, and assumes that the additional time can generate income at £2 per day. The "village wage rate (maintenance)" is the rate that someone would be employed to be the local person that can solve minor problems, provide first line training, and is set at twice the village income rate figure.

Interest paid to village shop is the percentage that the shopkeeper receives from collecting the interest payments on a new product and is set to 33%.

Village shop share of product profit is the amount of profit the shopkeeper receives as a percentage of product sales profit, set to 50%.

Gross Interest. This is the APR equivalent. The calculations use the assumption APR% = 2 × simple interest rate.

Village shop share of kerosene sold is the amount of income the shopkeeper looses by not selling kerosene for lighting lamps and is set to 25% based on informal discussions in Hagam (Nepal) in 2007 [8].

Village share of wage profit is what the shopkeeper keeps for employing maintenance people in the village and is the difference between wage rate paid and income received by the employee.

Pico_hydro_country_coverage the average amount of energy that can be generated from pico-hydro power = 3%.

Average cost of training per person is the total cost to train each person at the village, shopkeeper, maintenance person etc. and is set as a one-off cost of £10,000 per person employed.

Core elec. Cost (normalised figures) is the cost per Watt of electricity generated of the basic technology (i.e. excluding parts common to most products) and is normalised to obtain like-for-like comparisons across products that require different operating regimes. Thermo-acoustics TRL2 is not normalised, but kept at 250 We. This gives a pessimistic figure for this technology. i.e. if normalised with other technologies, it would look better; the reason being that it assumes an increase in electricity use and so the energy generated figure is 250 We to meet this demand.

Hob (i.e. the part that heats the pot) prices vary considerably; an average value of £10 is used for each case.

AHX or ambient heat exchanger is required for all heat engines to dissipate heat. The lowest quote we could find for a unit that could perform this function was for an aluminium automotive radiator available in Tajikistan for $8 the quote was received from a colleague Mark Loweth. The extra cost of connecting pipes etc. increases the cost to £8 and this figure used in all heat engine products.

Balance of plant. The balance of plant cost used in this paper is from a market survey undertaken by Mr Taif Hossain Rocky of Practical Action Bangladesh in December 2012 [27]. Detailed breakdown of costs used is contained in the Excel™ model. Other costs are estimated as: LED lights £3 each, rechargeable torches £2.00 each.

6.1.2. Photo-voltaic TRL9

There are a number of complications when assessing the ownership cost of PV installations. The cost per peak kW for PV systems has been rapidly reducing over the last 2 years and prices are likely to fall further. Weather conditions can affect energy delivered from PV cells by a large factor. As well as daily variations such as cloud cover, reductions in received light during different seasons have a large effect; winter and rainy seasons are some examples. Bangladesh weather was used to calculate required panel size, being typical of a sunny developing country. Panel efficiency is worse in summer than winter due to higher temperatures and mono-crystalline silicon will generate much less electricity than the designed value. On a diffuse day in July, (summer) output drops to less than 1% of a sunny day [28]. The best output on a sunny day in summer was 250 Wh/m^2/day at a tilt angle of 30degrees and is the figure used in this paper. We assume that the panel is tilted with the season to improve efficiency but not over a course of a day. The calculations assume that the minimum 150 Wh average per day is delivered over 2 days, one diffuse, one rainy, requiring 300 Wh on the sunny day, which gives a solar panel of 1.2 square metres or 120 W peak (Wp) at 100 W/m^2. Reichelstein [29] has analysed large-scale PV installations and quotes a "sustainable figure" of (1.35 $ per Watt peak) 0.84 £ per Wp for the basic modules excluding electronics and installation. The model normalises each product to 50 W over 3 h. So the normalised £ per Wp is £2 per Wp. Battery size for the PV system has to be twice the size of the baseline to cope with one day of dull weather.

6.1.3. Pico-hydro TRL9

The basic pico-hydro units themselves are quite cheap and are available from a number of vendors. Most costs are incurred from installation and that varies from site to site. A 2001 estimate gave a figure of £1.9 per Watt ($3000 per kW) [30] and a more recent survey [31] in Andean, South American, says $2.3 per Watt to $2.6 per Watt when fully installed. The model uses a figure of $2.5 per Watt. An evaluation in Thailand [32] gives a higher figure of 11.25 pence per kW h, which is between the model prediction of 8 pence per kW h capital only repayments and the 30 pence per kW h fully burdened price. The Andean survey estimates that about 7–15% of energy for people not connected to the mains grid could come from pico-hydro; the Andean region having a plentiful supply of water. The IPCC in a wider survey [33], estimates total hydropower for non-OECD countries is 2.8% but with a wide variation between regions. The model uses a figure of 3%, but this can be changed according to the region under investigation.

6.1.4. Thermo-acoustic

All thermo-acoustic products are at an early stage of development. The method used to evaluate production costs is briefly described in Ref. [8]. The Score-Stove™ design of Chen and Riley was constrained by capital costs and so efficiency is low, but still comparable to thermo-electric design. They used this method to evaluate the costs for a Score-Stove™2 [34] which was audited by a team of 6 people at a large blue chip engineering company that included professional engineers and cost estimators. The audit results are contained in Appendix A. With the Chen Riley design, the audit estimated a volume cost of £150. By using cost-reduction techniques, a value of £60 may be obtainable. We assess the £150 figure as being TRL4 and by subtracting balance of plant costs arrive at a figure of £2.34 per Watt generated if the target of 50 W can be achieved. The £60 figure requires more work so we have assessed it at TRL level 3, which gives a figure of £0.5/We. The record for a high-efficiency thermo-acoustic engine is held by the Chinese Academy of Science at 18% thermal to electricity output [35]. This is assessed as TRL level 2 and the same figure of £ 0.5 per We is used for this variant. The CAS design is expensive and not suitable for this application. However, preliminary work by Kees deBlok of Aster Thermoacoustics has suggested that a high-pressure engine could be designed with a much higher efficiency using the low-cost Score manufacturing technology. Its implementation is some years away, but it does show a path for a higher output product that is not yet available from the other heat engine technologies investigated.

6.1.5. Thermo-electric TRL8

Costs for the TE option was taken from the commercially available Bio-Lite stove which in Jan 2013 was selling for £80 ($129) generating 2 W continuously of electricity [36]. Assuming a 50% reduction for bulk purchase and cost reductions gives £40 and subtracting the cost of common features of £33 gives a module cost of £3.66/W. This gives a more realistic and comparable cost than taking the wholesale costs of the thermo-electric (TE) module, as TE performance is highly dependent on heat exchanger efficiency and electrical power de-ratings needed to prevent failure due to exceeding the rated temperature. Lertsatitthanakorn amongst others has done work evaluating TE performance in representative environments [37].

6.2. Results

The tables below follow the sequence of the calculations from the bottom, (householder) up to government level, based on Table 1, the product price assumptions. The model is contained in a publically available spreadsheet [19] with each formula and connections between levels clearly annotated.

Table 1
Assumptions contained within the model for this paper.

		£	
Oil price	$100.00	62.5	per barrel
Kerosene to oil ratio	90%		
Litres per Barrel	159	litres per barrel	
CO2 per litre	2.7	kg per litre	Kerosene
Retail Price Kerosene	1	£	per litre
House hold kerosene PM	2	litres per month	
house hold oil saved per year	9.4	£ per year	
Gross borrowing interest	15%		
Current wood use	3	kg per day	
Stove improvement	50%	less wood used	
Maintenance cost percentage	10%		
Battery life	3	years	
Product life Score and Thermoelectric	10	years	
Cookstove life	3	years	
picohydro life	20	years	
Carbon credit	0.10	£ per kW h	
People per household	4	People	
Village wage rate (maintenance)	1460	£ per year	
Village income rate	730	£ per year	
Amount of interest paid to village shop	33%	of interest received	
Village shop share of product profit	50%	of product profit	
Village shop share of kerosene sold	25%		
Village share of wage profit	50%	difference between wage rate paid and income rate	
Pico_Hydro_country coverage	3%		
Average cost of training per person	10000	£	

Table 2
Product price comparisons.

	Thermo-acoustic TRL4	Thermo-acoustic TRL3	Thermo-electric	Solar option 1	Clean cook stoves	Pico hydro	Thermo-acoustic TRL2	
Generating capacity	50	50	50	50	0	50	300	We
Reduction in deforestation	548	548	548	0	548	0	548	kg per year
Costs								
Hob	10	10	10	0	10	0	10	£
AHX	8	8	8	0	0	0	8	£
elec. generating technology	117	27	183	100	N/A	78.1	150	£
Balance of plant	15.1	15.1	15.1	15.1	0	0	30	£
Core technology total	150	60.1	216	115	10	78.1	198	£
4 off 3W LED	12	12	12	12	0	12	12	£
2 off rechargeable LED torch	4	4	4	4	0	0	4	£
7AH Lead Acid deep cycle battery (3)	12.1	12.1	12.1	24.1	0	0	12	£
Product wholesale cost	178	88.1	244	155	10	90.1	226	£
Installation and training	2	2	2	2	1	2	2	£
Transport	2	2	2	2	1	2	2	£
Profit	17.8	8.81	24.4	15.5	1	9.01	23	£
Total selling price	200	101	273	175	13	103	253	£
Package price	200	101	273	188	N/A	116	253	£

6.2.1. Product view

The price of the thermo-acoustic TRL2 is most expensive at £253. However, this generates 300 W of electricity so the price per Watt is the cheapest (see tables below). As the goal is to provide both clean cooking and electricity for lighting to remove black soot from kerosene use, the solar option1 and Pico-hydro have been combined with a clean cookstove in the package price and the clean cookstove alone is not included. The selling price includes transport to the village and profit for the shopkeeper.

6.2.2. Household view

The BoP household is taken as the metric in Table 2, which computes the figures required to payback the micro-finance loan (labelled "bought on HP", i.e. hire purchase) for the packages described in Table 1. Repayment is shown yearly for clarity on later tables, whereas in practice this is likely to be monthly or even weekly as preferred by the household. A solution is considered affordable if yearly cost minus income is less than zero and hence no subsidy is required. Where income is higher than expenditure the subsidy is shown as zero.

The thermo-acoustic TRL2 predicts the lowest cost per kW·h generated. However, this technology is unproven and being at an early release level would require significant research and investment to make it a reality. The next cheapest option, pico-hydro shows 12 h of electricity use per day, as although cooking is only for 3 h, the electricity is available for use when required. However, this is not a universal solution due to lack of suitable water flows. In climates where there is sun for most days, the solar/clean cookstove is the cheapest available option. The currently available (i.e. no development investment is required) option for general worldwide use is thermo-electric.

6.2.3. Village view

Taking the individual costs in the householder view (Table 2), and separating out those costs that affect the shopkeeper, produces Table 3. All options are affordable as they generate more income

Table 3
Business model of the effect on a typical householder.

Householder finances	Thermo-acoustic TRL4	Thermo-acoustic TRL3	Thermo-Electric	Solar option 1	Clean cook stoves	Pico hydro	Thermo-acoustic TRL2	
Initial capital investment (bought on HP)	200	101	273	175	13	103	253	£
Capital payback	20.0	10.1	27.3	17.5	4.3	5.2	25.3	£ per year
Interest payment	15.0	7.6	20.4	13.1	1.0	7.7	18.9	£ per year
Maintenance cost	20.0	10.1	27.3	17.5	1.3	5.2	12.6	£ per year
Battery replacement (3 years)	1.9	1.9	1.9	2.8	N/A	N/A	0.9	£ amortised pa
Total yearly cost	56.9	29.7	76.8	50.8	6.6	18.0	57.8	£ per year
Income (not buying kerosene)	24.0	24.0	24.0	24.0	0.0	24.0	24.0	£ per year
Income (increase in earnings as less wood to collect)	5.2	5.2	5.2	0.0	5.2	0.0	5.2	£ per year
Carbon credit	5.5	5.5	5.5	5.5	0.0	6.1	33.2	£ per year
Total Income	34.7	34.7	34.7	29.5	5.2	30.1	62.4	£ per year
Subsidy required	22.2	0.0	42.1	21.3	1.4	0.0	0.0	£ per year
Use per day	3.0	3.0	3.0	3.0	0.0	12.0	3.0	Hours
Energy generated	54.8	54.8	54.8	54.8	0.0	60.8	328.5	kW h per year
Oil saving	9.4	9.4	9.4	9.4	0.0	37.7	56.6	£ per year
Cost per kW h	1.04	0.54	1.40	0.93		0.30	0.18	£ per kW h

Table 4
Business case for the whole village.

Number of households in village	500							
Total village income	365	£k per year						
	Thermo-acoustic TRL4	Thermo-acoustic TRL3	Thermo-electric	Solar option 1	Clean cook stoves	Pico hydro	Thermo-acoustic TRL2	
Loss in income due to reduced sale of kerosene	−3.00	−3.00	−3.00	−3.00	0.00	−3.00	−3.00	£k per year
Share of interest received	2.48	1.25	3.37	2.16	0.16	1.28	3.13	£k per year
Share of product sales profit	0.89	0.44	1.22	0.78	0.17	1.50	1.13	£k per year
Share of people employed	5.11	2.92	6.57	4.38	0.73	1.46	4.75	£k per year
Net income generated	5.48	1.61	8.16	4.32	1.06	1.24	6.00	£k per year
Maintenance people employed	7	4	9	6	0	2	4	people
Installers employed (steady state)	7	4	9	6	2	2	9	people
Total people employed	14	8	18	12	2	4	13	people

than is lost from kerosene sales. The highest income option for him is the thermo-electric. However, this is not affordable for the household without subsidy. Pico-hydro alone generates the least income.

6.2.4. Regional or country view

In Table 4, the cost of each package is multiplied by the number of households in the region to compute the total capital investment required. The capital low cost and generating capacity of pico-hydro is because suitable water sources are not generally available and so a "% coverage term" is included in the model to reflect this. For a solution to be affordable at the country level, imports should be greater than or equal to exports. The computation of this figure will depend on how much of the product and its associated profit is manufactured and retained within the country, is highly dependent on governmental policies and national skill levels, and so the exact computation is outside the scope of this paper. However Table 4 does give details to make such a computation. Aggregating the power generated by each stove shows the equivalent of a 500 MW electricity generating plant for most options. If most of the stove manufacturing could be made in country, and taking into account the capital saved in building a 500 MW plant, it could be possible for the reduction in oil imports to match the specialist parts that would need to be imported to manufacture the stoves (see Table 5).

7. Discussion

On the one hand, there is evidence that there was cooking in China by Homo erectus over 400 thousand years ago. The World Bank states "Research on improved cookstoves dates back to the 1950s; the ensuing decades witnessed large-scale field programs centered [sic] on increasing the efficiency of certain stove designs. Over the past 30 years, the focus of the international community has gradually shifted toward the socio-cultural contexts in which the stoves operate. While the stoves themselves may have been simple, their effects on household and regional health and economics have often been complex and far-reaching. In short, many approaches to introducing improved stoves have been tried, with some successes and many failures… From 1980 until about

Table 5
View of impact on the whole country (or region of a large country).

	Thermo-acoustic TRL4	Thermo-acoustic TRL3	Thermo-electric	Solar option 1	Clean cook stoves	Pico hydro (1)	Thermo-acoustic TRL2	
In a region of	10	10	10	10	10	10	10	Million households
For a capital investment of	2000	1009	2725	1747	130	31	2527	£ million
and a return on investment of	10%	10%	10%	10%	10%	10%	10%	
Capital payback amortised over 10 years	200	101	273	175	13	3	253	£ million per year
The following can be achieved								
Reduction in oil imports	94	94	94	94	0	11	566	£ million
Generating capacity	500	500	500	500	0	15	3000	MWe
Generating energy	548	548	548	548	0	18	3285	GW h per year
Reduction in CO_2	648	648	648	648	0	19	648	k tonnes CO_2 per year
Reduction in deforestation	5	5	5	0	5	0	5	M tonnes per year
Jobs generated	280	160	360	240	40	2	260	Thousand people
Cost per kW h	1.04	0.54	1.40	0.93		0.30	0.18	£ per kW h
Ongoing Subsidy required	221	0	421	213	14	0	0	£ million per year
% product produced in country for zero balance of payments	53%	7%	66%	46%	N/A	0%	0%	
Subsidy (if not affordable)	221	0	421	227	N/A	0	0	£ million per year

2002, hundreds or even thousands of artisan-produced cookstove models were developed…" [38]. Whereas mobile phone uptake in poor rural areas has increased from almost zero in 2007 to over 50% in 2012.

A product that reduces total household air pollution (HAP) and is rapidly accepted by stakeholders, such as the mobile phone, would have a very significant impact on global health. By analysing more holistically the lifestyle of rural households, this paper provides a methodology for increasing the affordability and sustainability of products that can reduce HAP. Combined with micro-finance, the barrier to purchase of a large capital product is removed, and by selection of suitable technology packages, the income-expenditure of the household is unaffected as the weekly payback of the micro-finance loan is balanced with the other financial changes. Each country has different requirements, and some may choose a more expensive technology but decide to subsidise the product. In other cases, the householders may choose to pay extra, in effect providing the subsidy themselves. The model provides a transparent method of making such decisions and the consequences thereof.

8. Conclusions

Current interventions outside China to provide clean cooking stoves have been both small in scale and the benefits to health uncertain. BoP rural communities have shown a willingness to embrace new technologies such as mobile phones, but less so with clean cookstoves, even though the latter have an immediate improvement on the user by reducing the smoke that makes eyes water and produces coughing. Initiatives such as the Global Alliance for Clean Cookstoves are not currently tackling the contribution from kerosene lamps to household air pollution, something that the author asserts is necessary to improve health. Large-scale health improvements will only come about with high volumes of product use. Product performance that meets the end-user requirements, affordability and stakeholder acceptance are three important drivers to large-scale acceptance. Villagers will normally buy the cheapest product even though this may not be the lowest cost of ownership in the longer term. The use of Micro-finance is becoming well established and removes the capital cost barrier. Through an understanding of the needs of the households and using a holistic approach, the right package of solutions is shown to improve the affordability, in terms of income – expenditure, even though initial capital costs are higher. The model can be used to predict the effects of changing the product packaging and of different technologies.

Villagers are aware of the benefits of electricity, particularly for lighting and charging mobile phones. Large-scale deployment of the packaged product decreases oil imports and provides income for all the stakeholders; the model is able to predict the effect on a country's balance of payments for each technological solution. The lowest electricity cost on a £ per Watt generated (of available products) is pico-hydro. However, when looked at as a solution for a whole country, this does not provide a complete coverage but should be implemented where possible. Thermo-acoustic TRL2, if it could be made to meet the requirements, would be the most affordable and the cheapest option, but considerably more investment in research and manufacturing tooling is required to realise this benefit. Clean cookstoves (minus electricity) although the cheapest option still requires a subsidy as its affordability rating is low due not being able to offset capital costs with lower kerosene use or electrical carbon credits. Additionally it may not deliver the health benefits expected. Thermo-electric requires the most subsidy to be affordable but is a solution that could be made available world-wide and with current technology. The Photo-voltaic cell/cookstove solution may be suitable in areas of high sunlight on most days.

Affordability is highly dependent on the amount of income that can be generated from carbon credits. In 2012 the market rate for carbon credits was very low. If the predicted increase in the price of this commodity increases, some options would not require additional subsidy to become affordable.

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Appendix A.

Results of an audit by an Engineering Team from a Blue-chip Powers Systems Manufacturing Company of Score-Stove™2 predicted the volume prices below, 12 July 2011.

(1) "Our best view of the current concept is that it will have a 'fully burdened' factory-gate selling price of circa £150 – transport and installation costs will be in addition. This is relative to a requirement of £25 for 80% of the target market, £40 for 10% and £60 for 3% and includes fixed cost contribution and a profit element. Even at this price the concept does compete with other technologies on a £/watt basis.

(2) The current concept requires more work to bring down costs further on requirements such as:

Radiative heat to cooking is reduced compared with conventional stoves – the solution to this is at the early point of testing, which is to pre-heat the air ahead of combustion by drawing it over the heat exchanger using natural aspiration and also by using cooking pots that sit into the hob to increase surface area for convective heating, hence achieving comparative cooking times.

Achieving the 100 W electricity target – 1.5 bar gauge mean pressure is required in the acoustic pipes; sealing issues need resolving to achieve this. Nottingham believes they will achieve 50 W at 0.5 to 1 bar gauge with current sealing techniques.

(3) Major ideas the audit team and Nottingham brainstormed for cost reduction could reduce the 'fully burdened' factory gate selling price to £60 with the major items as below. (At £60 the stove would hit 3% of the market, which would be circa 15 million units).

By using mass manufacturing techniques and automotive process it was thought that the following higher cost items could be significantly cost reduced:

- Radiator (using modern automotive aluminium design).
- Regenerator (by lower cost material).
- Convoluted heat exchanger (using mass production techniques and supplying directly from the foundry).

However whether these gains can be realised is uncertain and requires significant R&T.

(4) Item (3) would provide electricity at £1.2 per Watt.

***********************************"

Appendix B. Technology readiness levels [23]

TRL 1	Basic principles observed and reported.
TRL 2	Technology concept and/or application formulated.
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept.
TRL 4	Technology basic validation in a laboratory environment.
TRL 5	Technology basic validation in a relevant environment.
TRL 6	Technology model or prototype demonstration in a relevant environment.
TRL 7	Technology prototype demonstration in an operational environment.
TRL 8	Actual Technology completed and qualified through test and demonstration.
TRL 9	Actual Technology qualified through successful mission operations.

Appendix C. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2014.06.050.

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