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Low cost solar thermal storage for time-shifted carbon free cooking

Smart Villages Research Group ltd

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Executive Summary

Heat from the sun for cooking is free. But often food is not prepared at times when the sun shines (eg in the evening) or in places where it shines (eg outdoors). This has led to low uptake of solar cooking technologies. But if simple technologies can be developed to capture and store heat from the sun during the day, for use later and in different locations for traditional cooking, this should provide a solution which is culturally acceptable and delivers significant development benefits. Those benefits include reducing indoor air pollution, and the health impacts that causes, reducing emissions of greenhouse gases and biodiversity impacts from wood;/charcoal gathering, and improving productivity and drudgery for women and girls, on whom the task of collecting cooking fuel often falls, with additional security risks from the long journeys required.

There has been some work done in this area, but solutions are often over-engineered and so unaffordable (the only solution on the market costs $300 per unit). It is possible to develop systems using less optimal, but much more affordable and less complex components. In this project we set out to investigate the performance and efficiency of different components of such a thermal storage cooking system, and how they might most appropriately be combined into low-cost appropriate systems. We tested them for performance and user-acceptability in Uganda and Tanzania with local partners, and investigated the potential for manufacturing them locally in microenterprises.

Cooking is a complex dance of energy flows. The most fundamental process in cooking is heating up water – either as a cooking medium, or water contained within foodstuffs. And heating water is a particularly energy intensive task. And in competing with fossil fuels and firewood, we are competing with fuels that are particularly energy intensive and portable. Trying to innovate a new approach that uses heat from the sun in a conventional cooking process involves trying to compensate for the huge heat losses in conventional cooking, from the use of uninsulated pots, to waste heat from the energy source. This means it is necessary to collect and store a great deal more energy than is required just for the pure cooking, because of the unavoidable losses in the system and processes.

We investigated cooking processes in communities our partners work in in both Tanzania and Uganda. Whilst not all their cooking events would lend themselves to using stored heat, at some would. We were able to find suitable local materials for thermal storage – blocks of stone or concrete up to 10kg will store enough energy to cook a family meal with appropriate insulation. Being able to find local material to provide good enough insulation to effectively store the heat for several hours without loss was much more difficult through. We could not achieve better than 50% heat retention over 4 hours. But the biggest challenge came from collecting the energy from the sun to charge the thermal storage devices. It proved eminently possible to build concentrators from local materials at low cost. But their physical characteristics – in particular their size and unwieldiness and lack of practicality – made them unsuitable for adoption by target communities.

We believe there are further design improvements that could be made, but at a household level such devices would still only be installed somewhere safely out of the way, such as on a rooftop. Possibilities exist to create entrepreneurial implementations of our approach – for thermal charging services to be established operating multiple devices, and providing charged thermal elements as a service. But this could only succeed commercially in an environment where fuel such as firewood is not available freely.

More interesting are the possibilities we begin to analyse for using the thermal storage elements with alternative heat sources, including industrial waste heat (eg from pyrolysers) or heat from electricity, especially in the context of surplus generation in minigrids. We believe it will not be possible to achieve widespread impact on cooking practices in the developing world using thermal storage charged purely from solar energy, but we believe that using these alternative sources of heat may have real possibilities, and is much more likely to lead to the environmental, social and economic impact we were hoping for in the this project.

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1. Introduction

1.1 Heat from the sun for cooking is free. But often food is not prepared at times when the sun shines (eg in the evening) or in places where it shines (eg outdoors). This is one of the factors which has led to low uptake of solar cooking technologies (others include the cost of novel solar cooking technologies, impracticality (size and mobility of solar cooking technologies), and sometimes unanticipated risks of technologies (for example the potential of parabolic reflectors to cause fires if stored carelessly where they will receive and focus sunlight).

1.2 If simple technologies can be developed to capture and store heat from the sun during the day, for use later and in different locations for traditional cooking, this should provide a solution, or at least an option, which is culturally acceptable and could deliver significant development benefits. Those benefits include reducing indoor air pollution, and the health impacts that causes, reducing emissions of greenhouse gases and biodiversity impacts from wood;/charcoal gathering, and improving productivity and drudgery for women and girls, on whom the task of collecting cooking fuel often falls, with additional security risks from the long journeys required.

1.3 Successful uptake of such a solution would of course further depend on other negative factors being addressed, such as cost, convenience and safety.

1.4 There has been some work done in this area, but solutions have tended to either miss the goal of working with existing cooking behaviours (for example low-temperature (c 120C) phase change materials being used to prolong the "hot" phase of solar ovens) or are excessively complex and unaffordable (the only solution currently on the market costs $300 per unit and relies exclusively on imported technology and components). It should be possible to develop systems using less optimal, but much more affordable and less complex components.

Aims of the project

1.5 In this project we wanted to investigate the performance and efficiency of different possible components of such a thermal storage cooking system, to establish overall feasibility of such components and the system as a whole, and we wanted to explore how the most appropriate and complementary of these could be integrated into low-cost appropriate systems. We planned to test them for performance and user-acceptability in Uganda and Tanzania with local partners, and investigate the potential for manufacturing them in-country in local microenterprises.

Objectives of the project

1.6 The design and evaluation of different techniques for concentrating solar thermal radiation for cooking purposes.

1.7 The evaluation of different materials for thermal storage of solar heat, for subsequent cooking purposes.

1.8 The evaluation of different materials for insulation of thermal storage material evaluated above

1.9 Characterisation of cooking behaviours and methods in target communities

1.10 Design of systems based on the three technological evaluations above to meet the cooking needs of test communities.

1.11 Consideration of the ability of materials to be locally sourced, and ability/capacity for local manufacturing.

2. Methodology

2.1 More than 3bn people still cook on inefficient biomass cookstoves, the smoke from which according to WHO research (2018) causes more than 4m deaths annually, in addition to climate change and biodiversity impact.

2.2 Even improved cookstoves still require biomass fuel, gathering of which is a significant and disproportionate burden on women and girls in rural communities, leading to impacts on (and withdrawal from) education and impacting productive time, safety and security (Welland, 2015).

2.3 There are innovative solutions for smoke-free cooking. But these often come at a high price point, or require a change of cooking culture. And some (LPG and biogas) still produce greenhouse gases (MECS TRIDS Grant Spec 2019).

2.4 Many rural areas in LDCs are in zones of high and reliable insolation. Solar cookers provide a means to cook meals at zero ongoing cost after the capital cost of equipment. There has not been widespread uptake, since use of solar cookers often involves a change in cooking practice and the time of maximum useful heat from the sun often does not match the time at which main meals are prepared (Solar Cookers International, 1998).

2.5 Thermal energy storage solutions for time shifted cooking, that “charge” with solar heat at times of maximum solar insolation, and release that heat later in the day for productive cooking could have the following advantages:

2.5.1 achieve biomass-free cooking which does not contribute greenhouse gases or degrade biodiversity, and does not adversely affect health through indoor smoke or require disproportionate amounts of women’s/girl’s time to gather firewood

2.5.2 achieve cooking at zero ongoing cost, after capital cost of equipment

2.5.3 with a portable thermal store, traditional cooking practices timings and locations can be maintained (eg indoors), which should lead to higher user acceptability.

2.6 A solution that combines affordable and locally appropriate technologies will perform less well than an optimally specified solution, but can still be functional. This is the solution we will be exploring in this project, which will have the two following additional advantages:

2.6.1 system affordability for all target disadvantaged communities – not just the wealthiest technology adopters in a community

2.6.2 technology transfer and enterprise generation – the ability to manufacture systems, and market and maintain them locally

2.7 Sunshine is free, and using heat from the sun to cook has health, productivity and gender benefits. At the moment, there is no simple affordable technology solution available to rural disadvantaged communities to use, alongside more traditional solutions and future innovations. Development of such an option could fill an important niche and provide an additional clean and attractive option, and achieve significant benefits.

2.8 Such systems are not universally useful though. In some places, sunshine is not reliable, or alternative energy may be abundant, with other solutions being preferable. But a low-cost time-shifted solar solution that requires minimal change to traditional cooking practice could play a valuable role in replacing use biomass cookstoves until superior technologies become available.

2.9 To address the potential downsides of using solar thermal energy to produce the stored heat, we also consider alternative sustainable sources of heat for thermal storage and time-shifted cooking.

Outline of the concept

2.10 Finding a solution to the challenge involves combining three distinct areas of engineering and technology – an effective, robust and low-cost (solar) thermal collector, a high-capacity, affordable and safe thermal storage medium, and low-cost, safe and efficient insulation to help retain the heat until cooking-time.

2.11 This is a poorly researched issue, and under-explored set of technologies. There has been a tendency to explore optimum solutions (hence the interest in materials science literature and phase change materials – which are undeniably attractive for high capacity thermal storage, but may be expensive and complex to engineer).

2.12 The only solution available commercially at present is the SUNBUCKET developed by a team from the University of Illinois. https://www.sunbuckets.com/

2.13 

2.14 This is an attractively designed but complex system using off-the-shelf parabolic reflectors and a phase-change storage medium, which they have tested in sub-Saharan Africa as well as in the US. But the unit cost for the system is $300 which potentially puts it out of reach of our target market in the developing world.

2.15 Solar cookers and solar cooking technology are still seen as a niche product, and little if any comparison research has been done. For example, the following are three of the most popular specifications for sub $10 parabolic reflectors (for direct solar cooking), but little detailed performance testing has been done.

2.15.1 The “Fun Panel” - https://solarcooking.fandom.com/wiki/Fun-Panel

2.15.2 The Solar Funnel Cooker - https://solarcooking.fandom.com/wiki/Solar_Funnel_Cooker

2.15.3 The Box Solar Cooker - https://solarcooking.fandom.com/wiki/Minimum_Solar_Box_Cooker

2.16 In this project we intended to examine the following:

2.17 **Solar concentrators**

2.18 Evaluate the performance of existing designs of solar concentrator, as well as innovative designs of our own, for efficiency, cost, ruggedness, adaptability (eg to different angles of the sun) and ease of assembly/manufacture.

2.19 For example, different designs not only collect/concentrate different amounts of solar energy, but perform differently according to angle of the sun and require more or less adjustment to track the sun. Some are efficient but – when made from low cost material – are very susceptible to wind or dirt. Some are effective but rely on exotic materials for their construction, which would need to be imported rather than being able to be manufactured locally. And most of the existing designs are aimed at direct solar cooking, which requires a subtly different focus of the sunlight as compared with solar thermal charging.

2.20 **Thermal storage**

2.21 Evaluate the performance of various substances and technologies, including low-cost phase change systems for heat capacity, cost, safety, suitability for cooking and ease of assembly/manufacture

2.22 Simple materials, such as concrete, rock and metal, have good thermal characteristics (available also from the literature) and are available locally. Phase change materials have the double advantage of a high thermal capacity and the characteristic of maintaining a single temperature during much of their thermal cycle. However, they can be expensive and complex to encapsulate. Most of the research and data available is aimed at large scale commercial thermal storage systems in the industrialised world (eg CSP plants).

	Temperature		Average density	Average heat conductivity	Average heat capacity	Volume specific heat capacity	Media costs per kg	Media costs per kWh_t
Storage Medium	Cold (°C)	Hot (°C)	(kg/m^3)	(W/mK)	(kJ/kgK)	(kWh_t/m^3)	(US$/kg)	(US$/$kWh_t$)
Solid media								
Sand-rock-mineral oil	200	300	1,700	1.0	1.30	60	0.15	4.2
Reinforced concrete	200	400	2,200	1.5	0.85	100	0.05	1.0
NaCl (solid)	200	500	2,160	7.0	0.85	150	0.15	1.5
Cast iron	200	400	7,200	37.0	0.56	160	1.00	32.0
Cast steel	200	700	7,800	40.0	0.60	450	5.00	60.0
Silica fire bricks	200	700	1,820	1.5	1.00	150	1.00	7.0
Magnesia fire bricks	200	1,200	3,000	5.0	1.15	600	2.00	6.0
Liquid media								
Mineral oil	200	300	770	0.12	2.6	55	0.30	4.2
Synthetic oil	250	350	900	0.11	2.3	57	3.00	43.0
Silicone oil	300	400	900	0.10	2.1	52	5.00	80.0
Nitrite salts	250	450	1,825	0.57	1.5	152	1.00	12.0
Nitrate salts	265	565	1,870	0.52	1.6	250	0.50	3.7
Carbonate salts	450	850	2,100	2.0	1.8	430	2.40	11.0
Liquid sodium	270	530	850	71.0	1.3	80	2.00	21.0
Phase change media								
$NaNO_3$	308		2,257	0.5	200	125	0.20	3.6
KNO_3	333		2,110	0.5	267	156	0.30	4.1
KOH	380		2,044	0.5	150	85	1.00	24.0
Salt-ceramics ($NaCO_3$-$BaCO_3$/MgO)	500–850		2,600	5.0	420	300	2.00	17.0
NaCl	802		2,160	5.0	520	280	0.15	1.2
Na_2CO_3	854		2,533	2.0	276	194	0.20	2.6
K_2CO_3	897		2,290	2.0	236	150	0.60	9.1

2.23

2.24 Candidate storage media for SEGS plants (Geyer 1991)

2.25 **Insulation**

2.26 Evaluate the performance of various substances and innovative designs for insulation, to maximize thermal charging of the storage medium, facilitate its transport (ie to move it from the solar collector into the house), and to maximize the period of heat retention for time-shifting cooking. Key characteristics include efficiency, cost, local availability, safety and ease of assembly/manufacture.

Material	Typical Thermal Conductivity (W/mK)	Commonly available forms
Natural Material		
Wood fibre	0.038–0.050	Boards, semi-rigid boards and batts
Paper (cellulose)	0.035–0.040	Loose batts, semi-rigid batts
Hemp	0.038–0.040	Semi-rigid slabs, batts
Jute	0.038–0.040	Semi-rigid boards, rolls and batts
Wool	0.038–0.040	Semi-rigid boards, rolls
Flax	0.038–0.040	Semi-rigid boards, rolls
Cork	0.038–0.070	Boards, granulated
Synthetic Material		
Mineral fibre	0.032–0.044	Boards, semi-rigid boards, rolls
Glass fibre	0.038–0.041	Boards, semi-rigid boards, rolls
Extruded polystyrene (XPS)	0.033–0.035	Boards
Expanded polystyrene (EPS)	0.037–0.038	Boards
Polyurethane (PUR)/polyisocyanorate (PIR)	0.023–0.026	Boards

2.27

2.28 Properties of insulation materials – Ghosh et al 2016

2.29 **System design**

2.30 From these three evaluations we intended to create, in discussion with our overseas partners, some alternative system designs and specifications to optimize performance, affordability and simplicity/appropriateness, using our skills in appropriate design of technology solution – developed during our work particularly with the University of Malaysia Sarawak in the creation of technology solutions for off-grid remote communities in the rainforest, where local reliability, affordability and maintainability were more important characteristics than pure efficiency and performance metrics.

2.31 For our purposes, a successful and appropriate system will be one that consists of a solar concentrator and at least two cooking/thermal storage units, which costs less than $50 and where each storage unit can be used to cook a full family meal when appropriately charged, and can retain 80% of its heat for at least 4 hours when insulated. This would put the system into a bracket of affordability matching clean cookstoves and pico solar home systems.

2.32 **Testing and Evaluation**

2.33 We planned to test these systems for performance and user acceptability in poor rural offgrid communities in Tanzania and Uganda where we have existing partnerships with local NGOs. In addition, in each location, we will work with the NGO partner and community members to determine whether it is possible to construct the designs from local materials, with a view to establishing a local micro-enterprise if user-testing is successful.

2.34 **Thermal Alternatives**

2.35 In order to explore the wider applicability of any systems or approaches we create, we also intend to examine other potential sources of thermal energy, to charge the thermal storage units, in the absence or unfeasibility of solar thermal radiation.

Intellectual Property Rights

2.36 We believe in open-source technologies for development, so will not be seeking to protect any technology solutions we develop.

3. Implementation

Where relevant, more data and findings are shown in the appendix.

The work conducted

3.1 Design and evaluation of solar concentrators – explanation of designs and construction materials and methods of different solar concentrators, including ones currently commercially available, with a summary of key characteristics.

3.2 Results of testing different designs of concentrator (in terms of heating value achieved for a standard amount of water over a period of time).

3.3 Choice and evaluation of thermal storage materials – discussion of merits and characteristics of different materials to store the heat, for subsequent cooking utility

3.4 Results of testing heating efficiency and heat retention of different materials under standard conditions.

3.5 Choice and evaluation of insulation materials – discussion of different materials tested, their merits and practical effectiveness

3.6 Results of testing insulation materials, using data for heat retention in a standard thermal material over time

3.7 Cooking behaviour studies – results of specific cooking behaviour studies in test communities, as well as more general data from other cooking behaviour studies that have been carried out elsewhere.

3.8 System Integration – options for combinations of components to meet possible needs/behaviours of target communities

3.9 Discussion of local availability of materials, local alternatives, and manufacturability of systems locally

3.10 Description of test principles and issues raised in user communities

3.11 Discussion of alternative implementation possibilities in user communities

3.12 Exploration of alternative sources of heat for thermal storage technologies, and testing results.

3.1 Findings: Solar Concentrators

3.13 To concentrate the energy from the sun it is necessary to transfer the incident radiated energy into a smaller area. There are two essential ways of doing this – with a convex lens, to focus down the energy into a point, or to accomplish the same thing with a concave mirror. Because of the relatively lower cost and ease of construction of simple mirrors, the tendency has been to use forms of parabolic mirror, which have the property of reflecting all incident radiation towards a single focal point. Thus a thermal load, either for heat storage or a cooking pot, placed at this focal point receives reflected radiation from the entire surface of the mirror, concentrating the energy so that it can lead to higher heat and effective cooking.

3.14 There are a number of parabolic reflectors on the market, for different purposes, as well as a number of hobbyist guides for building low cost parabolic solar cookers. Our intention was to evaluate these alternatives for their effectiveness of delivering concentrated heat to standard volume of water in a cooking vessel, or a standard mass of thermal storage.

3.15 The alternatives evaluated were:

3.15.1 Fun Panel Solar Cooker[1] – a hobbyists self-build out of cardboard and aluminium foil (although we used corrugated plastic board of a similar stiffness and thickness to cardboard, for ruggedness). The thermal load rests on a portion of the reflector, on the ground.

3.15.2 Funnel Solar Cooker[2] – an improved hobbyists self-build out of cardboard and aluminium foil. Similarly, the thermal load rests within the reflector on the ground (or on an insulating base)

3.15.3 Adapted parabolic reflector – satellite dishes are parabolic reflectors, and are commoditised to the degree that they are available at extremely low cost. We used a commercially available 80cm satellite dish and stand, costing just £35, and covered the inner face with aluminium foil

3.15.4 Commercial parabolic reflector cooker – a large off the shelf 1.5m diameter parabolic reflector cooker

3.15.5 Constructed parabolic reflector – homemade parabolic reflectors made out of precision cut "petals" made from cheap, readily available material eg cardboard (again, we used corrugated plastic board). We tried small and large versions of the reflector.

3.15.6 Large tensioned reflector panel – as an alternative to engineering a perfect parabolic dish, using flat sheet material (plywood) laminated with reflective foil, and using tensioned wire to bend the sheet into a curve to focus the incident radiation. We mainly tested this reflector when the sun was not at high inclinations, with the thermal load on the ground, though to use it properly, the load should be supported in the focus with the reflector having the ability to tilt.

3.15.7 Large tensioned double reflector panel – one problem that emerged with many of the parabolic options was the difficulty of supporting the mass of the thermal load at the focus of the parabolic mirror. An alternative, rather like a double reflector telescope, is to have a primary mirror to reflect and partially focus the incident radiation upwards, and then a smaller secondary reflector to reflect and continue to focus that radiation back downwards, through a hole in the centre of the primary. In this way, the thermal load is behind the primary reflector, and can even be on the ground.

3.16 Discussion of characteristics of the alternatives

3.16.1 Relevant characteristics of the alternatives we were evaluating were thermal performance, stability, cost, complexity, local manufacturability and reliability. A table of these characteristics is provided in the appendices.

3.16.2 On price, of the options that worked, the two hobbyist's reflector cookers came in at the lowest cost level, of under £5 each. The tensioned plywood panel was also low cost (£10) although for effective longer-term use a mounting frame would also be needed. On the more engineered side, the satellite dish was surprisingly good value at £35 including a robust stand. Bearing in mind that this also incorporates shipping costs and profit margin, it demonstrates the value possibilities that manufacture at scale could bring. The commercial solar cooker, at £120 was the most expensive option we tested. Though at three times the surface area (and therefore cooking power) of the satellite dish, it is not that much more expensive than triple the price of the dish (which would be £105) for an engineered solution.

3.16.3 Stability was the next important criterion, and demonstrated the trade-off between the simple and the engineered solutions. Although we were constructing and testing the different options in conditions of low wind, it was surprising how susceptible the hobbyists' versions were to even

[1] https://sites.google.com/site/suncookers/pictoral-guide-to-building-a-fun-panel-cooker
[2] http://solarcooking.org/plans/funnel.htm

gentle breezes. The two simple solar cookers would only work reliably with a great deal of bracing with sticks, otherwise they blew over or collapsed. We can only conclude that the photos and tests that are available of these cookers freestanding on their own are carried out in conditions of zero wind.

3.16.4

3.16.5

3.16.6 *Constructing and testing the hobbyists' solar cookers in Tanzania*

3.16.7 The constructed parabolic reflector only had structural integrity when it was relatively small. Any size above 50cm led to a lack of rigidity, and our efforts at constructing a mirror more than 1m in diameter proved impossible. In order to try to stabilise the shape of constructed mirrors this size, we had to use so much bracing and support on the rear of mirror, including high tech materials such as expending building foam, that it would not be easily or cheaply replicable in the field. Our conclusion is that this form of construction would only work for a mirror of "useful" size if the petals were made of a more rigid material (eg rigid plastic sheet, multiwall polycarbonate, or sheet metal).

3.16.8

3.16.9 The tensioned reflector panel was extremely large (2.4m x 1.2m) and therefore also proved to be susceptible to wind, but had very good structural coherence. With sufficient bricks and wooden poles to anchor it, it was possible to stabilise it in the wind. However, it was clear that to be able to control it to track the sun would require a more sophisticated mounting frame, and in turn therefore a structure to hold the thermal load at the focus of the reflector. A suitable mounting structure was also problematical for the double reflector concept, where it became clear that the most important criterion was to precisely lock the positions of the primary and secondary reflector with respect to each other, in a structure which could tilt to follow the sun.

3.16.10 The two engineered reflectors had a high degree of structural integrity but were still susceptible to wind (the sail effect) and required bracing to prevent movement in the breeze. A further problem for both was the mass of the thermal load. We tested the alternatives with either 1 litre of water in a metal cooking pot, or a 2.5kg cast iron block. Both engineered solutions struggled to reliably support these weights at the optical focus of the mirror.

3.16.11 In terms of complexity, the engineered solutions and the hobbyists' versions won out. Although both had structural issues, these were of a lesser order of magnitude than the degree of bracing and framing support that the other solutions required.

3.16.12 For local manufacturability, it was surprisingly easy and quick to assemble the hobbyists' solar cookers, and the tensioned reflector panels. The engineered solutions (or an engineered solution to the self-constructed parabolic reflectors) would obviously require importation – neither of our partners believed there was the capacity to press/mold sheet metal in-country – or less accurate and more expensive panel beating. It would be possible to assemble suitable mounting frames locally – welding shops existed in both communities in which we were working. But this clearly increases cost and complexity.

3.17 Performance of the alternatives

3.17.1 For thermal performance, a further consideration was loss of heat to the atmosphere and the ground. Following suggestions online, ground supported thermal loads were placed inside heat-resistant transparent oven roasting bags, to prevent excessive heat loss from convection, and placed on insulating material to prevent radiative heat loss to the ground. For the engineered reflectors, the best solution found was to place the thermal load using stand-offs inside a pyrex container at the optical focus of the reflector to cut down radiative and convective loss.

3.17.2 Both hobbyists' cookers successfully heated water to boiling point, though it was impossible to maintain these temperatures for any length of time because of wind instability, unless the cookers were constantly supervised and repositioned. The reflective plywood sheets were also able to heat a thermal load (iron block) to temperatures of over 100 degrees, but the difficulty here was being able to track the sun for long enough and maintain the focus on a ground supported thermal load. The focus of the plywood sheet reflectors was also much less precise than the parabolic reflectors, so positioning was more important. Experiments where the reflectors could be angled to follow the sun, and where the load was supported in the focus of the reflector, were promising, but we found it difficult to reliably support the load in this position. A welded structure would probably be necessary to maintain this degree of support and rigidity, but we were unable to test this within the confines of this project.

3.17.3 The smaller engineered reflector was unable to easily support loads of more than around 1kg at its focal point, which made even smaller thermal loads particularly vulnerable to heat losses to the surrounding air. The larger reflector cooker was able to support our chosen load of 2.5kg iron block within a pyrex container, and successfully heated this to 212 degrees even during the northern winter with the sun at angles below 20 degrees. Because of the size of this device, it was not possible to take it and test it in Africa at higher elevations of the sun. But keeping the load stable was a problem even here. We predict that trying to keep loads of a greater mass stable in the focus of this reflector could be challenging, without significant structural augmentation to the supports.

3.18 Recommendations for use/integration

3.18.1 The essential finding of this portion of our research was the tremendous difficulty in making a suitable reflector for concentrating the suns energy. In an ideal system, the reflector should have the greatest possible surface area. However in practice this makes it structurally unstable, unless it is constructed from extremely rigid materials which are more expensive and less likely to be available locally in developing countries. Furthermore, and more importantly, the size of these reflectors then makes them more difficult to handle and store by end users, as well as making them very vulnerable to the effects of even quite small amount of wind.

3.18.2 Our conclusions are that it is very difficult to find a design and materials that will allow for the construction of a device large enough to successfully heat a thermal storage load to temperature above 300 degrees, without resorting to expensive, higher tech materials such as fibreglass or formed sheet metal. And even these are unwieldy and present storage and safety issues when they are not being used, since accidental exposure of the reflector to the sun risks concentrated solar energy causing burns or fires

3.2 Findings: Thermal Storage Media

3.19 A good storage medium for thermal energy should have a reasonable thermal conductivity (so that it can absorb and release the heat effectively), have a high heat capacity, be affordable and easy to source locally, and be able to release a useful amount of heat to a cooking load. It is unfortunate that water has a relatively high specific heat – 4.18kJ/kgK or 1.16Wh to raise the temperature of a kilogramme of water by one degree Celsius. This is higher than the specific heat of most other candidate substances for thermal storage – the specific heat of cast iron for example is 0.45kJ/kgK, and most stones, brick and concrete materials are between 0.8-0.9kJ/kgK. This means that, in order to effectively cook by boiling water requires either a thermal storage medium at a very high temperature, or of a much greater mass than the food/water combination. High temperatures come with their own dangers, but too high a temperature risks melting the cooking vessels, or burning the food. The attraction of solid-liquid phase change materials is that they harness the latent heat of solidification of the material to greatly increase their thermal capacity, so that lower temperatures and mass of storage material become a possibility. Solar salt (a non-eutectic mixture of $NaNO_3$ and KNO_3) is reported to have a specific heat of around 1.5kj/kgK, and a latent heat capacity of around 150kj/kg. In other words, the energy it releases on solidification is equivalent to the energy released in cooling down by 100 degrees.

3.20 Cooking processes like frying, or baking, since they do not involve boiling volumes of water in the same way, are thermally easier. But since stewing and boiling are among the most prevalent cooking processes used in our target countries, we will seek to establish the effectiveness of materials for these heat-intensive processes. In considering the efficacy of thermal storage, it is also important to appreciate that thermal transfer into cooking is not a perfect process. There is a great potential for heat loss not just from the thermal storage medium, but also from the cooking vessel itself. In an ideal world, the pots would be insulated and pressurised, but this project aims to study the capacity for heat storage materials to allow cooking with existing equipment and processes. So there is a great deal of heat loss from the cooking vessel itself, making it important that the thermal storage medium is able to transfer heat into the cooking vessel faster than it is lost by radiation and convection.

3.21 The alternatives evaluated were:

3.21.1 Cast iron – mild steel has a slightly better heat capacity than cast iron, but proved much more expensive to source. For the purposes of this project, therefore, we just used the cast iron.

3.21.2 Stone – one problem with natural stone, on consultation with experts – is that different rocks have very different characteristics under heat. In particular, many types of rock may split or otherwise deform under intense heat. Basalt – a volcanic rock – was therefore chosen as the most thermally stable easily sourced rock.

3.21.3 Concrete and brick – these building materials also have some structural issues under intense heat (more for concrete than brick) but since their performance was very similar to the performance of rock, we stopped using these after initial testing.

3.21.4 Phase change material – there are many different phase change materials available, which can be tuned to a range of precise temperatures, but also have relatively higher costs. The most appropriate low cost material to use may be the "solar salt" mixture referenced above (60% $NaNO_3$ and 40% KNO_3). This is thermally stable to above 500 degrees, and ha a melting point of 250 degrees. But for simplicity, we used pure KNO_3 which has a higher melting point (around 330 degrees) but decomposes at 400 degrees. Because of this decomposition, this material would not be suitable for solutions made available for end use.

3.22 Discussion of characteristics of the alternatives

3.22.1 The relevant characteristics we are looking for are the heat capacity of the materials, their ability to transfer that heat into water for cooking, practicality of use and their cost and availability in target communities. Stone or concrete are easily available at low cost in target communities – although the thermal qualities of the stone and the concrete would need to be tested before adoption, to ensure they would crack under operating heat. Block of metal are less readily available, but may be sourced at medium cost from junkyards or metal fabricators. High tech phase change materials are difficult to source. But – although we were not able to investigate the possible supply chains for simple salts such as KNO_3 or $NANO_3$ – these materials are generally available from specialist suppliers in country, and can relatively simply be melted, and encapsulated in a welded metal container. Even with simple phase change materials, this is the most expensive and costly option however.

3.23 Performance of the alternatives

3.23.1 The major issue for thermal performance was heat loss – both in the heating phase (as discussed in the previous section) and the use phase. During use in a cooking environment, a great deal of heat is lost from the thermal storage medium itself, as well as from the sides and top of the cooking vessel. To optimise the cooking process, an insulated container for the thermal storage material would be important to try to ensure as much energy as possible can be transferred into the cooking vessel, rather than being lost from the base and sides of the material. We simulated this as best possible by placing insulating material below and around the candidate storage materials when testing their heat transfer capabilities.

3.23.2 The materials all performed well at taking up thermal energy. The metal had the greatest conductivity, and took up heat the quickest (owing also to the fact it had the lowest heat capacity of any of the materials tested). Basalt was the slowest to absorb the heat, which was also a factor of its lower density, which made heat losses from radiation and convection all the more important during the heating-up phase. Because basalt is less dense than metal, it was also more challenging to keep it insulated, eg in a pyrex dish) using solar heating.

3.23.3 Metal was the fastest material to transfer its energy into the water for cooking. The stone performed noticeably slower, though was then able to maintain the temperature for longer, since it had a greater amount of energy stored. Neither set of materials were able to boil a litre of water when heated to 200 degrees. The highest temperature achieved was 78 degrees, regardless of our efforts to better insulate the systems. The heat loss from the system over the time taken was just too great to allow the water to reach boiling point. When heated to 400 degrees, it was possible to boil water, although the thermal losses during this phase were considerable (we estimate from theoretical calculations of the stored energy levels, that at least 70-75% of the stored heat energy from stone elements is lost, and around 50% of the energy from metal. The loss is lower in metal because the higher thermal conductivity heats the water up more quickly, so there is less time for radiative and convective losses).

3.23.4 *[A note on insulation:- The purpose of this project was to try to innovate an approach that would let communities use traditional cooking methods with a different source of heat. It is for this reason that in our main tests we utilised simple, uninsulated pots and un-optimised surface contact correlation between the storage media and the cooking vessel, since it mirrors actual cooking behaviour and technology. But it is for this reason that the losses were so high. In an adoption-ready system, it would be possible to better correlate the surface area of the thermal storage element (eg by casting concrete into a cylinder of different dimensions to match pot size) or by providing sufficient top-insulation to the storage element to only expose the appropriate size area to the cooking vessel (as we tried to do in as many of our tests as possible). Insulating the cooking vessel may be much more problematical, however. With local insulation materials it is difficult, if not impossible, to insulate the vessel from high temperatures in excess of 200C. If the insulation is not in contact with the high temperature heating element, more basic insulation becomes a possibility (in a way that it is not currently possible, with an open fire). This does involve behavioural change in cooking habits though, and additional complexity. An enveloping insulation system might keep more heat in, but may make it harder to observe the stages of cooking, impede ability to stir the food, and may need frequent cleaning from spillage – but we believe it is likely that communities would be receptive to some form of innovation like this that could be constructed locally: a thick fabric pad, for example, that could wrap around the cooking vessel to at least insulate the sides, without impeding the top of the vessel).]*

3.23.5 An interesting alternative approach to heating water, without the same degree of heat loss, is to borrow from ancient cooking practices and use the thermal storage materials as cooking stones. Heating smaller (500g) pieces of basalt to 200 degrees and placing these directly into the cooking vessel results in very rapid heat transfer (under a minute) and use of 8 of these in succession was able to bring 1 litre of water to the boil (from 13 degrees) in an uninsulated pot. Obviously, for adoption of an approach like this, the stones need to be kept very clean.

3.23.6 Being able to start with boiling water in this manner results in a further utility improvement of the approach, since it is easier to maintain the temperature of a cooking vessel than to raise it. Using a 10kg basalt storage element at 200 degrees made it possible to maintain a litre of water at boiling (simmering) point for 100 minutes, with very gradual cooling after than (<5 degrees per 15 minutes). This timescale would be perfect, for example, for the more energy-intensive cooking tasks like making beans.

The thermal testing set-up we used in the UK – we insulated the exposed areas of the thermal storage media which were not in contact with the cooking vessel, but did not insulate the vessel, to mimic current community practice. We used a glass lid where possible, since it let us take IR thermometer readings without needing to remove the lid.

3.23.7 Phase change materials performed better than the locally available materials, as expected. But high heat losses occur in the system nevertheless, so the main advantage to using phase change materials is that the mass of the thermal storage element can be lower (in our experiments, the mass of KNO_3 required to perform an equivalent amount of heating to basalt was 50%. Thus 3 kg of phase change salt did as well as 6 kg of basalt (other phase change materials perform even better – for example the solar salt mixture referenced above). This clearly makes a difference if it is necessary to support the thermal storage medium at an elevated position, in the focus of a parabolic reflector. But it makes little difference for ground based thermal loads (other than the slightly smaller size makes it easier to insulate)

3.24 Recommendations for use/integration

3.24.1 The materials performed well – for ease of local sourcing, rock or concrete are clearly to be preferred, though in order to achieve decent cooking performance a relatively high mass of these materials is necessary (at least 10kg – more depending on the volume of food to be cooked). Phase change materials of course perform better – in our example we were able to achieve equivalent heating with just half the mass of phase change material, compared to stone. But this only really makes a difference for thermal mass which needs to be suspended and mobile, to track the focus of a parabolic reflector, for example. If thermal storage materials can be charged whilst on the ground, there is little advantage (unless there is a much larger heating requirement, for example for institutional cooking, where the necessary mass of stone or concrete could become difficult to move).

3.3 Findings: Insulation Material

3.25 There are two major reasons for requiring insulation material. One is to retain as much of the heat in the thermal storage material as possible – both to increase the length of time between heat absorption and use, as well as to increase the amount of energy that can be transferred for cooking, by cutting down thermal losses in other directions from the storage material. The second purpose is to protect the user, and make it safe to handle a high temperature material, and to use it in the home.

3.26 In general, as well, a greater thickness of insulation works better. But if the insulation around a thermal load is too bulky, it will make it difficult to handle. So ideally, the volume of the insulation would be no greater than five times the volume of the thermal storage medium.

3.27 The alternatives evaluated were:

3.27.1 Mineral wool – domestic roof insulation material 300mm thick

3.27.2 Expanded polyurethane insulation board – domestic wall insulation 60mm thick

3.27.3 Fireplace insulation blanket – aluminium silicate boiler and fireplace insulation and fireproofing blanket

3.27.4 Vermiculite – exfoliated vermiculite, as a natural high temperature insulating material, is being tested as a proxy for local analogous mineral insulating materials, such as fine pumice pebbles

3.27.5 Natural organic materials, such as wood, straw etc

3.28 Discussion of characteristics of the alternatives

3.28.1 The characteristics we were examining, in addition to thermal performance, were physical performance, cost and local availability, and safety of use. The three artificial materials, mineral wool, insulation board and fireproofing blanket would all need to be imported, and would therefore have the highest cost and be least convenient. A natural pumice is readily and cheaply available in Tanzania, which we believe would perform analogously to vermiculite. But no such material is easily available in the communities we were working in in Uganda.

3.28.2 The natural organic materials were extremely susceptible to high heat, which made them combust or char. Solid wood was interesting though. That only charred on the surface, and even then particularly when the thermal storage medium was directly in contact with it. Potentially, a box made of wooden planks, internally lined with a layer of clay, could be an effective transport solution for the thermal storage blocks, even if it would have a role in longer term insulation.

3.28.3 Of the artificial materials, only the mineral-based ones performed reliably. The polyurethane foam boards thermally decompose at around 200 degrees, releasing some extremely unpleasant fumes, so are unsuitable for use.

3.29 Performance of the alternatives

3.29.1 Of the three remaining insulation materials that went through to testing (mineral wool, aluminium silicate blanket and vermiculite), performance was relatively close. The mineral wool performed the best, even though its structure renders it very liable to compression under heavy loads. Potentially therefore, this would be a less suitable material for base insulation of the more massive thermal storage blocks. The fireproof blanket and vermiculite are much less susceptible to structural deformation under load.

3.30 Recommendations for use/integration

3.30.1 The most striking finding of this aspect of our research is that it was not possible for us to find an insulating material that would perform anywhere close to our original intended benchmark of retaining 80% heat over 4 hours. All of our tests showed losses of over 50% in four hours. The only way to improve this is to have the full insulation in-situ during the heating phase (so that the thermal storage medium is not losing heat to establish the thermal gradient across the insulating material, which is the case then the thermal storage block is placed into "cold" insulation) and to make the insulating layer much thicker. Neither of these solutions lend themselves particularly to ease of use, however.

3.30.2 A conclusion from this set of results, therefore, is that in order to effectively achieve the time-shifting part of the cooking, the thermal storage medium must be charged with at least double the amount of energy it will need (including losses) to achieve the ultimate cooking task.

3.4 Findings: Cooking Behaviour Studies

3.31 In both Uganda and Tanzania, our partners work in deep rural areas. Communities are predominantly agricultural/livestock focussed, are off the electricity grid, lack mobile signal, and either have poorly maintained dirt roads, or no roads at all to connect them to the outside world.

3.32 In Tanzania, our partners work with Maasai communities in the Simanjiro area, on the plateau around 2 hours south of Arusha. Communities are chiefly livestock oriented, with little agriculture (some small subsistence cropping does take place). Sub-villages consist of a number of reasonably widely dispersed bomas, which are thorn-fence enclosed groupings of up to 10 houses, accommodating one two large family groupings between them.

3.33

3.34 The predominant method of cooking is via a three stone stove, which are outside the home. The predominant fuel is wood, which is gathered from the surrounding countryside. Since the wood is becoming rarer, it can take quite a while to collect the firewood. The usual foods prepared include ugali, vegetables, rice, maize, beans, porridge and tea.

3.35 The wife of the sub-village chairman described her typical cooking behaviour to us. She goes out into the bush to collect wood for cooking every two days, but her older relatives who are less strong (and can carry less) have to go every day. The further advantage of being younger, is that you have young children who can accompany you and can help collecting and carrying. She cooks three times a day. The day starts with tea and porridge, which requires a shorter cooking process. Lunch/afternoon will typically include beans and therefore takes longer to cook. The evening meal will also be large, and take longer to cook, since leftovers will be eaten cold in the morning. A longer cooking activity will typically take 2 hours during the dry season, but when the firewood is wet, it more usually takes 3 hours from start to finish. Addition cooking work derives from cultural factors, including that men by tradition cannot eat alone, and it is also important to offer hospitality to strangers who may be passing.

3.36 

3.37 *Community discussion in Tanzania*

3.38 One of the leading women in a neighbouring community described typical woman's day as follows:

3.38.1 Wake at 5am to milk cows

3.38.2 6-8am make breakfast and feed family

3.38.3 8-11am load donkeys and fetch water from nearby river

3.38.4 11-2pm cook main meal and feed family

3.38.5 2-5pm collect wood in bush around village

3.38.6 5-7pm cook dinner and feed family

3.39 In Uganda, our partner works with more remote communities in Luweero and Nakaseke districts, some two hours north of Kampala in the Central Region of Uganda. Communities are mainly agriculture oriented, with some cash crops and livestock in addition to subsistence crops. Villages consist of up to 250 households at medium density (houses can be 50-100m apart). The predominant method of cooking is by three-stone stove, most of which are outside the home, using firewood or charcoal fuel. Usual foods include matooke (banana), posho, sweet potato, yam, beans, and vegetables.

3.40 We spent less time in the communities in Uganda, so did not get as detailed a set of process descriptions of cooking practice. However, the majority of households in the communities with which our partners work have one main meal a day. The time of preparation of this varies, but is usually at lunchtime or early-mid afternoon. It will typically take 2 hours to prepare this meal, depending on exactly what it consists of.

3.41 The Ugandan communities in which our partners work would, ironically, be good candidates for direct solar cooking solutions as well as using more concentrated heat from a thermal storage device. There is less need for time-shifting however, which could ameliorate the downsides of inefficient insulation materials available locally. In Tanzania, the lunchtime or afternoon meal could similarly lend itself to preparation with direct solar cooking or non-time shifted cooking using thermal storage devices. The evening meal is a more classic case for using thermal energy in a time-shifted manner. It is hard to see, however, how thermal storage could work to help prepare the breakfast, since this would require the thermal storage element to be maintained at temperature overnight (albeit tea and porridge could potentially be made without needing to boil water – temperatures or 50-60 degrees may suffice for this)

3.5 Findings: System Integration Options

3.42 To combine the elements of a system together, it must combine optimal elements of each component type together in a system which is practically useable and effective. In the case of the Sunbucket solution, they have combined the commercial parabolic reflector together with a phase change material for heat storage, in an attractive carrier device which presumably incorporates a degree of insulation. This achieves some optimal aspects of performance, but at the expense of the system cost, and ability to produce it locally.

3.43 It would be interesting to further investigate supply chains to establish whether phase change materials can be obtained locally and cost effectively. At UK prices, it is possible to assemble a small phase change-based thermal storage element at cost of around £10 (the wholesale price of the nitrate salts discussed is under £1/kg, and even over the counter they are available for under £5/kg). We believe two kilos of a suitable salt mixture, heated to between 300 and 400 degrees, should be sufficient to cook a family meal for 4. Small metal dishes for encapsulation are available at around £1 in the UK, and such dishes are widely available in markets in Africa.

3.44 If we were to adhere to our original objective of solely using locally available materials, the optimum solution would be to construct a reflector out of a large sheet of plywood with a reflective layer bonded to it. Local stone or concrete are the most appropriate thermal storage materials. In the absence of a sufficiently rigid frame to support the thermal storage load in the air at the focus of the reflector, a ground-based solution is the most practical, albeit that means that it is difficult to harness the full power of the midday sun. In order to be effective, a mass of 10kg of concrete or stone is an ideal compromise between thermal capacity and portability (though difficult to support at height for the focussed midday sun), and if appropriately insulated can be heated to over 300 degrees in 2-3 hours with a 2m2 reflector. An advantage of concrete is that it will be straightforward to cast this in a block of the appropriate size, with (metal) handles for portability.

3.45 Encapsulating and insulating a mass of this size is a challenge. For transport and use, a wooden plank box internally lined with a layer of local clay should be effective. The only easily locally available insulation materials are the pumice-based vermiculite analogs. These are loose pebbles, however, so challenging to combine into a neat system solution together with a 10kg concrete mass. The most straightforward solution is to place the thermal storage mass into a specifically molded clay container surrounded by and holding back the pumice pebbles. There is a further challenge of a solution like this, however, in ability to tilt the system to receive solar radiation which is eg being reflected sidewise.

3.46 As is clear, there are still several significant compromises in being able to assemble a system out of optimised local materials. The most significant improvement to such a system would be the successful design of a double reflector system. This would mean a thermal storage mass that could remain on the ground, embedded in a suitable insulating system which need not be mobile, which opens up the possibility of significant improvement to the insulation performance in the system.

3.6 Findings: Local Manufacture Options

3.47 It was surprisingly easy to source some of the local materials for assembling the reflector systems. Plywood, reflective foil, and adhesives were all easy to obtain in Tanzania (and often at a lower cost than in the UK). Local welding capacity was also available, and had we had more time on the ground with our partners, it is likely that a suitable tilt structure and thermal load suspension frame could have been welded to our specifications on site. Rock is easily available, though would have to be cut or chiselled to size and shape (eg a flat surface for cooking). Concrete components are readily available though, although some locally available cement is not of the highest quality.

3.48 The biggest challenge for local manufacture is the insulation material. All high temperature high quality insulation material would need to be imported. The only material locally available is the pumice pebbles in Tanzania. Whilst these have possibilities in static insulation systems and do not perform much worse thermally than artificial materials, they are difficult to integrate into portable solutions. If we were to manufacture systems locally that required high performance insulation, importation might be the only solution.[3]

3.49 

3.50 The local manufacturing skills and capabilities are readily available. Our local partners and community members were enthusiastic in assisting in the production of reflectors and in making the hobbyist's solar cookers, and were able to suggest their own improvements and adaptations in very little time. Local welding and concrete casting capacity is also available for metalwork.

[3] The complexity of importing material is mainly to do with logistics and capital. The material itself is cheap, but a shipping container of mineral wool is likely to cost some $15,000 including purchase price, shipping, customs and delivery, and the process is complex.

3.7 Findings: User Interest/Testing

3.51 We involved the members of the local community and partners in our initial construction and testing of system components like the solar reflectors. They were enthusiastic about the principle – especially of the simple solar cookers, whose applications they immediately understood. However, they were extremely sceptical about the stability and practicality of the devices.

3.52 Within hours of beginning to test the solar cookers, they were suggesting that – if only it were possible to manufacture these out of metal, they would have real possibilities. They appreciated the potential of the larger plywood sheet concentrators, but were highly sceptical of the practicality and "fiddliness" (need to constantly adjust for solar angle and wind movement) of the systems. Their scepticism of these systems was such that they did not believe it would be worth testing them for proper cooking applications, as they believed the time and effort taken to try to use them successfully would be disproportionate to the benefit.

3.53 If it were possible to produce an easy-to-use system that did not require constant attention, and was safe eg for their children to be around, they would be more interested. A further challenge in the communities in Tanzania was that the firewood was essentially free (although very time consuming to collect). But this meant there was little economic imperative for finding and testing alternative solutions, especially if this did not involve significant increases in eg cooking efficiency (by contrast, there was a great deal of interest in electric cooking, when electric rings were discussed, because of the higher speed of cooking this involves).

3.8 Findings: Alternative Use Practice

3.54 The limitations that emerge in perception and practicality of our approach all relate to the solar concentrator. In conventional cooking practice, all the individual components (fuel, stoves, cooking vessels) are compact and easy to use. Dangers do arise from the smoke and the heat, and there are many injuries – especially to children – attested to by interviews with our user communities. But the danger elements (fire, smoke) are in known locations and are visible, so it is possible to eg try to teach young children to avoid the dangers

3.55 Our thermal storage devices, and their insulation containers, are equally compact and easy to handle. Whilst the high heat of the storage element is a risk, it can be mitigated by good practice (keeping it in the insulated container) and education about the risk involved. However, the third element of the system, the solar concentrators, are where the problem lies. Of necessity, these have to have a large surface area. The larger the surface area, the greater the heating capacity and speed, which in turn simplifies their use (since, for example, faster heating means less need to keep turning the collector to face the sun). Our own experiments demonstrate how easy it can be to construct large solar concentrators out of locally available low-cost materials. However, the downside of this approach is a lack of robustness. Our test systems were extremely vulnerable to wind and even imperfect placement on the ground could change their shape and degrade their effectiveness.

3.56 Making the collectors more robust, aside from cost implications, involves a significant increase in weight and complexity (for example, the need for stronger and more sophisticated ground mounting structures). It is this weight, bulkiness and inconvenience that make them unsuitable for widespread domestic adoption. Added to this, there are two further risks of even this more robust approach: firstly, the problem (which had already been identified at the start of our report) of storage. Where can bulky solar reflectors be stored when they are not being used, where they will not deteriorate in adverse weather, but where the risk of fire from accidental reflections/concentrations can be minimised? Recall early solar cookers using parabolic dishes had a tendency to set houses on first when they accidentally reflected sunlight onto structures. The second problem is one of positioning. Simple concentrators will necessarily reflect sunlight back up or, depending on orientation, sideways. Thus a mounting structure rigid enough to hold the thermal storage unit is necessary. But for large solar concentrators used in domestic spaces, there is also a risk of people (especially children) walking between the reflector and the focus, and injuring themselves. Unlike the earlier risks of burns from fires, the concentrated sunlight is invisible, making the risk much higher.

3.57 These issues make the adoption of systems for domestic users very unlikely. We can see two possible ways forward that would allow domestic users to nevertheless operate their own systems safely and conveniently:

3.57.1 refraction rather than reflection. Constructing optically effective and robust mirrors is challenging, as we have seen. However, if large lightweight magnifying lenses were more generally available, these would be much easier to use, and would allow the thermal elements to remain safely on the ground. Solid glass or plastic lenses of such a scale (>1m2) are clearly not practical for rural deployment. But large fresnel lens technology is a real possibility. Some work has been done by hobbyists in this area, using salvaged screens from broken large projection television units, to reasonable effect. Replacement screen units retail for around $100, but it is possible that simple Fresnel lenses of sufficient quality for heating purposes could be produced (at volume) at lower costs. Based on our estimates, we believe a solar thermal storage cooking system using Fresnel lenses could be marketed at under $150, if the lenses can be produced.

3.57.2 two-mirror systems. Having a double reflector would allow the thermal element to remain safely on the ground, and the light paths to be contained, making it harder for people to injure themselves, and eliminating the risk of inadvertently setting fire to property. A double mirror system, however, calls for even greater optical precision, and therefore robust construction methods, which would increase costs. Such a system would also have a bulk and weight that would require it to be static rather than mobile (but it could, for example, rotate to face the sun). Nevertheless, we could foresee a role for systems such as this installed, for example, on the roofs of houses or in other locations where they were not in the way. Such systems could probably be marketed at under $200.

3.58 An alternative approach would be to use the inherently-risky and bulky systems away from domestic users and members of their households, in order to eliminate the risk. In certain circumstances, for example where firewood and other sources of fuel are scarce or high cost, and solar energy is abundant, we could see the possibility of solar thermal entrepreneurs establishing solar reflector "farms" on land away from village centres, where multiple robust reflectors can be sited to simultaneously "charge" multiple thermal storage elements.

3.59 The operators of such sites, as energy entrepreneurs, would expect to dedicate time to frequent optimal alignment of the reflectors, and replacement of thermal storage units when fully charged, and ongoing repair and maintenance of the systems, so the "inconvenience" factor also disappears.

3.60 We could imagine such a model operating on a "subscription" basis – where users pay a weekly or monthly fee for a daily charged thermal unit (or multiple daily units, for each meal). An outline cost modelling of such as scenario (assuming a £100 capital outlay for a system which can thermally charge two storage units in a day, for 250 sunny days per year) shows that charging £0.07 (c TSh200) per charged device would repay capital costs in three years. This is the same order of magnitude as families are willing to pay for fresh water, which shows it is theoretically possible for them to afford to pay this amount (although, for cooking, we would be competing with "free" firewood).

3.9 Findings: Alternative Heat Sources

3.61 The problems we have found with the approach in our project mainly stem from the impracticality of the component to gather the heat – the reflector. It is worth therefore considering other sources of heat.

3.62 The main existing source of heat is the three stone fires themselves. It would be possible to place small thermal storage blocks around these fires to collect and store the heat that escapes sideways in existing cooking processes. It is not clear how much could be reliably gathered or stored in such a scenario, however.

3.63 A very promising alternative source of heat could be pyrolysis. There is a great deal of research ongoing (including by partners of SVRG) on designing efficient pyrolysers which could operate in a village setting in the developing world, fuelled by agricultural wastes, and produce electricity. A byproduct of these devices is high-grade heat, however, since they operate at 400-500 degrees. In principle, it should be possible to use this heat to "charge" thermal storage elements, which could then be transported into the home for clean cooking purposes. And since the pyrolyser operates around the clock, there is no particular need for insulation or the time shifting component. This also means the cooking process would be more efficient, since the element would not cool down very much from its original temperature. And of course, therefore, the "difficult" meals like breakfast could also easily be cooked with stored heat rather than using open fires.

3.64 A further alternative would be to use electrical energy, from photovoltaics in an offgrid setting, to supply the heat. A traditional solar energy system, incorporating complex components like charge controllers and inverters to power AC cooking devices is likely to be unaffordable. But there are a number of alternatives.

3.65 

3.66 To test the efficiency and cost effectiveness of a solar PV scheme, we directly coupled a 1600W (nominal) string of solar panels (generating 285vdc open circuit voltage, 214 vdc load voltage) to a simple £16 1.5kw AC cooking ring. The heating element worked perfectly under DC conditions (though it is important to note the dangers of high voltage dc, and the additional precautions that need to be taken – for example, the voltage arced across the simple AC switches in the socket we used). The ring itself rapidly reached a temperature of 426 degrees, was able to boil a litre of water within 7 minutes, and was able to heat up our 2.5kg cast iron thermal storage element to 440 degrees within 40 minutes (though this did require some insulation, to prevent heat loss to the air – the maximum achieved in free air was 356 degrees). We purchased our panels off the shelf. Wholesale rates, though, for solar PV are 40c per watt. For under £400 therefore, it would be possible to create a dc system that could directly electrically cook a lunchtime/afternoon meal for one family, but could also charge 4 thermal storage elements in the course of a sunny day, thus meeting the cooking needs of 2 or three families.

3.67 

3.68 More realistically, one of the challenges of trying to implement electrical cooking solutions in a community minigrid is the simultaneous high load drawn by each family cooking concurrently. At the same time, however, one of the challenges for minigrids is matching the supply to demand throughout the day. Thermal storage may be a way to address both these challenges. If spare electrical capacity can be directed to well-insulated thermal charging solution (cheap electric rings running at low power, for example), then over the course of a day many thermal storage units could be charged from the marginal extra capacity in the minigrid, and then used for more efficient low-carbon cooking without placing a direct cooking load on minigrid supply or (expensive) battery capacity. The exact operational economics and thermal capacity would of course depend on the specifics of the community and minigrid in question.

3.69 These alternative possibilities are important. The basic principle of cooking with stored heat is sound – our challenges at the moment concern mainly the ability to easily obtain that heat from solar heat. If alternative sources of heat are available (especially those which do not require any time shifting, such as the pyrolyser) then these could be even more effective ways to help the transition to cleaner cooking practices.

Limitations of the innovation/approach/design/system

3.70 One significant problem of researching solar thermal energy issues is, unsurprisingly, the availability of sunshine. In retrospect, generating significant results in just 6 months, in particular over the Northern Winter period, was always going to be challenging. As it happened, unusually poor weather in the UK meant that very little solar testing could be done at our base, and we had to carry out most of the significant solar experiments at our partner's site in Tanzania. The positive angle of this was that local community representatives were able to be present even for our own technology test, which allowed them to give their honest views on the technology before a specific user testing phase was due to commence.

3.71 The second problem related to the technology of the solar collectors – in this case, making solutions more affordable seemed to go hand in hand with that solution being less robust, and since surface area is key, more effective solutions became increasingly unwieldy. This was a critical aspect for user acceptability. Making the most appropriate technology designs more robust (and therefore also more precise), and more controllable is possible. But, for example, forming those components out of pressed steel sheeting involves an increase in cost, efficiencies of cost that only come with high volume, and a loss of ability to manufacture locally.

3.72 Nevertheless, the ubiquity and free availability of solar heat continue to make solar thermal energy inherently attractive. Future interesting technical development possibilities would include manufacture and testing (at a small scale, so clearly without the cost benefits of volume) more precisely manufactured, robust and controllable versions of optimum bi-reflective system designs, and also of the community entrepreneurial solar-thermal charging station concept, where insulated thermal cooking elements are then rented to users and recharged each day.

3.73 Following up the more positive findings, the area of electric heating of thermal storage elements seems a very promising one. It would be interesting to explore this further, in particular to investigate how thermal storage media might be charged from surplus minigrid capacity, and even improve the sustainability of minigrids without adversely affecting more usual electrical loads and productive uses.

4. Practical applications of the concept to the national cooking energy system (including costs)

4.1 Our initial findings are that a low-cost solar thermal storage solution is unlikely to be able to make a difference to national cooking systems at this stage, because of the complexity of managing the solar concentrator element.

4.2 However, the feasibility of thermal storage for cooking, and the possibility of doing this at an affordable cost, has been illustrated in this study. In order for this to make an impact on national cooking behaviour, we just need to find an alternative or more workable source of the thermal energy, or radically innovative technology (like low cost large Fresnel lenses) to harness the heat from the sun.

4.3 A community solar thermal charging station, operated safely and expertly by a solar thermal entrepreneur, could have impact, but since thermal “charges” would have to be paid for (for example on a subscription model), this is only likely to succeed in countries or regions where solid biomass fuel is not readily available for gathering free-of-charge. And unless sunshine was guaranteed year round, a hybrid business-model would need to be innovated whereby, eg the entrepreneur would undertake to provide fuel wood or charcoal if cloud-cover meant that thermal charges were unavailable that day. We calculate that a charge of £0.10 per day should enable this model to operate successfully (higher if capital costs are met by microfinance or a bank loan).

4.4 Thermal charging from an artificial heat source in the community, especially if that heat is a waste or by product, is a promising possibility for impact on cooking behaviour. For example, if a community (rural or urban) had an industrial plant such as a power station, or pyrolyser, or other process that involved high and constant heat, waste heat could easily be harnessed to heat small domestic thermal storage modules with a near guarantee of regularity, for distribution (paid or unpaid) to local community members. Since these approaches would be harnessing mainly waste heat (though there needs to be a balance, to ensure that the thermal “charging” does not remove so much energy from the system as to negatively impact the main process), charged thermal units could be provided more cheaply to customers. We calculate a daily cost of £0.03 or less for a unit could be possible.

4.5 And finally, though more investigation is needed, thermal storage technology could increase the impact and feasibility of use of off-grid electricity systems for domestic cooking, by charging thermal storage units throughout the day, using low levels of continuous electricity. This may in some circumstances prove a more effective route for electric cooking in offgrid situations than trying to use the electricity to cook directly, where overload of limited generation and distribution capacity may arise from high demand from multiple users simultaneously. And since there is the possibility for them to use marginal surplus minigrid capacity for charging, a marginal rate could also be charged for the electricity used in the thermal charging process. We calculate that rates as low as £0.05 per charged unit might be possible.

5. Next steps (further development etc)

5.1 Although this study has not evidenced the success of individual solar thermal storage systems for cooking on a household level, we hope that the proof of concept of the time-shifting/storage elements of the system will lead to increased interest in thermal storage solutions for cooking.

5.2 Although further R&D on a community entrepreneurial solar thermal charging "hub" would be interesting, we believe it is likely that this would only have limited appeal, in those rural areas where wood or other fuels are hard to come by. Wood, charcoal and other solid fuels are so energy-dense, and easy to use, that there is a significant barrier to overcome to persuade people to use alternatives. In order for that to happen, the alternatives need in particular to be as easy to use, and not be significantly more expensive or dangerous.

5.3 Similarly, to enable individuals to adopt solar thermal cooking technology more easily, further R&D on lens-based technology would be interesting. The challenge here is not so much the cooking system, as finding a way to manufacture large Fresnel lenses cheaply.

5.4 Using waste heat from other industrial processes is a very attractive proposition. SVRG is working with another partner who is developing improved pyrolysis technology, with a view to deploying this technology in development contexts to provide rural energy access. We intend to complement our existing partnership activities (which are in the context of a number of InnovateUK grants) with a test of thermal storage devices for community cooking, when the devices are ready for user testing.

5.5 The potential for use of offgrid electrical energy for thermal charging is a very interesting proposition. We believe that this could be a particularly powerful mechanism for leveraging thermal storage to change national cooking behaviour, given the prevalence and popularity of energy access schemes. And we believe that thermal storage may be an innovative way to avoid the problems of system overload in other, more direct, approached to offgrid electrical cooking (especially where the whole community is likely to want to cook at the same time). Potentially, being able to carry out thermal charging at a low electrical load throughout the day, or to be able to flex the charging to complement dips in demand from other productive uses and domestic use of minigrid power (and eg, to be able to charge units overnight in a minihydro grid) could contribute significantly to the operational and commercial performance of the minigrids, since the load profile could be smoothed and matched perfectly to generation with a flexible thermal charging load.

5.6 SVRG is currently working with a number of partners to develop a project to construct and demonstrate a number of mini-hydro based minigrids. If successful, we intend to test an overnight thermal charging/time-shift cooking solution as part of this project. We also note that the previous round of the InnovateUK Energy Catalyst competition had a special focus on storage-related projects. If the next round also has such a sub-focus, we intend to apply to this competition with a proposal to further develop and test electrically-based thermal storage cooking technology. We shall also seek opportunities from any other funders to pursue this idea further.

Dissemination Plan

5.7 Our website – e4sv.org – is currently under redevelopment. As soon as the new version is launched, by April, we will publish this report and a number of articles about specific elements of this research. At this stage, we are not intending to publish our full findings elsewhere, but we do believe that certain aspects – for example the potential of electrically-driven thermal storage – should be more widely appreciated, and so we will look for opportunities, through webinars or posters, to disseminate this aspect of our work more widely.

6. Conclusion

6.1 Cooking is a complex process. It is steeped in culture and tradition, which dictate its processes and habits. But even the science and technologies that underlie cooking as a process are a chaotic and byzantine combination of transformations of energy from one form to another, balances of energy flows and losses, and thermal and chemical performance of a vast range of different materials. None of this evident when we light a gas hob, or when a woman in Africa lights a three stone fire to prepare the evening meal.

6.2 We set out in this project to prove that it was possible to use energy from the sun to store heat during the day, and release that heat later for cooking in a manner that would avoid the use of unhealthy and environmentally damaging carbon-intensive fuels. And more particularly that it was possible to do this in a cost-effective manner using locally available materials and skills.

6.3 We have accomplished some of that objective. It is certainly possible to use local materials to store heat and to cook effectively using that heat rather than a three stone fire or cookstove. Local stone or concrete are the best materials to use for this (the ease of use of the concrete being counterbalanced by its negative environmental credentials), and whilst their effectiveness is certainly lower than high technology solutions like phase change materials, they are more cost effective and easier to produce locally.

6.4 We have uncovered particular challenges though in finding locally available materials to provide good insulation, allowing for longer time-shifting periods from heat storage to use. All the best and most portable materials need to be imported.

6.5 And most importantly, whilst the potential for using local material and skills to build effective solar collectors and concentrators is there, the resulting systems are currently not fit for purpose at a domestic level, due to their size, bulk, requirement for constant supervision, and potential safety risk.

6.6 We have been able to identify some limited use scenarios for some of the solar concentrator solutions, such as commercial thermal charging facilities, and improving the design of a dual-reflector system. But more interestingly, we have described some alternative sources of heat energy that could be used to more effectively charge thermal storage units in a way which we believe would make such systems better suited and more attractive for adoption by end users. These sources include waste heat from industrial processes such as pyrolysis, and electrical heating utilising spare capacity of minigrids.

6.7 We intend to investigate both of these possibilities in the future.

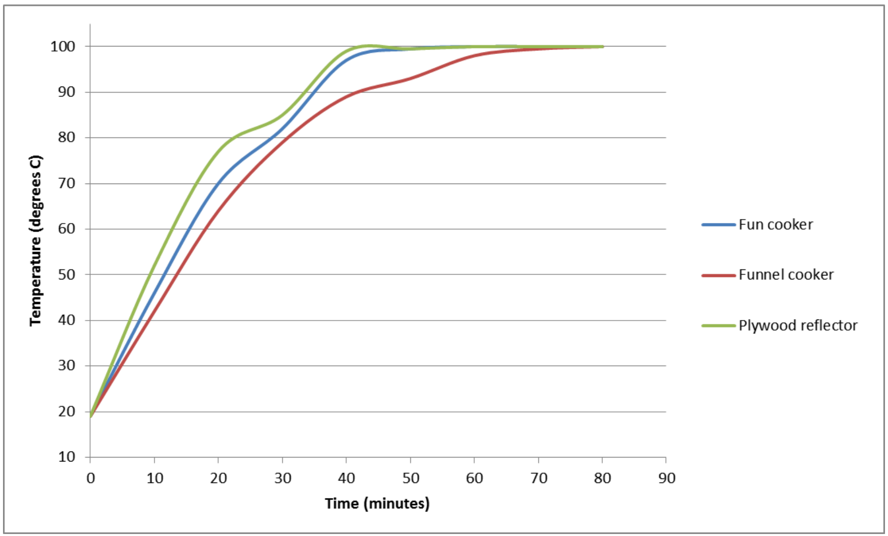
7. Appendix

7.1 Paragraph 3.16 – characteristics of alternatives for reflector/concentrators

Solar concentrator option	Thermal performance	Stability	Cost	System complexity	Local manufacture	Reliability
Fun panel cooker	Good	Medium	$	Low	Good	Poor
Funnel cooker	Good	Medium	$	Low	Good	Poor
Plywood sheet reflector	Good	Good	$	High	Good	Poor
Constructed parabolic dish	n/a	Poor	$	High	n/a	Poor
Small engineered dish	Good	Poor	$$	Medium	Poor	Good
Commercial solar cooker	Good	Medium	$$$	Medium	Poor	Good
Double reflector	Good	Good	$$	High	n/a	n/a

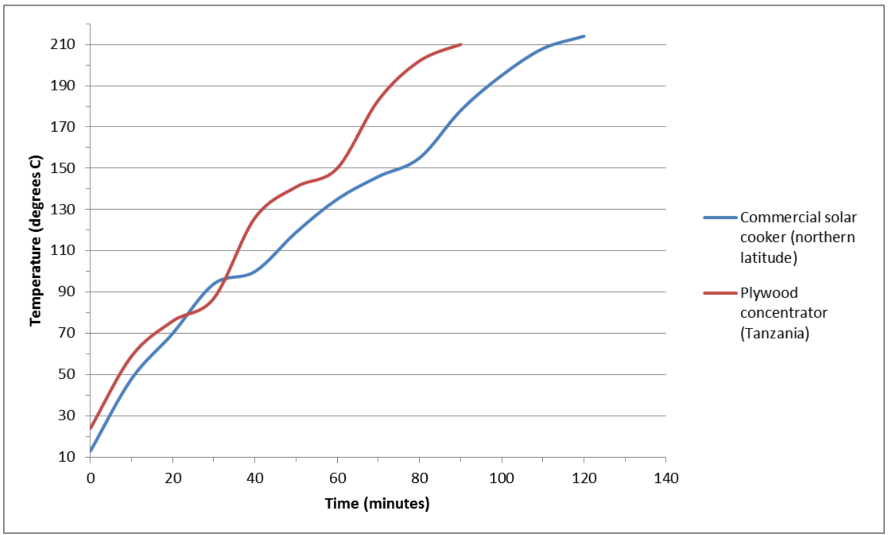
7.2

7.3 Paragraph 3.17 – efficacy of solar reflectors/concentrators in boiling water



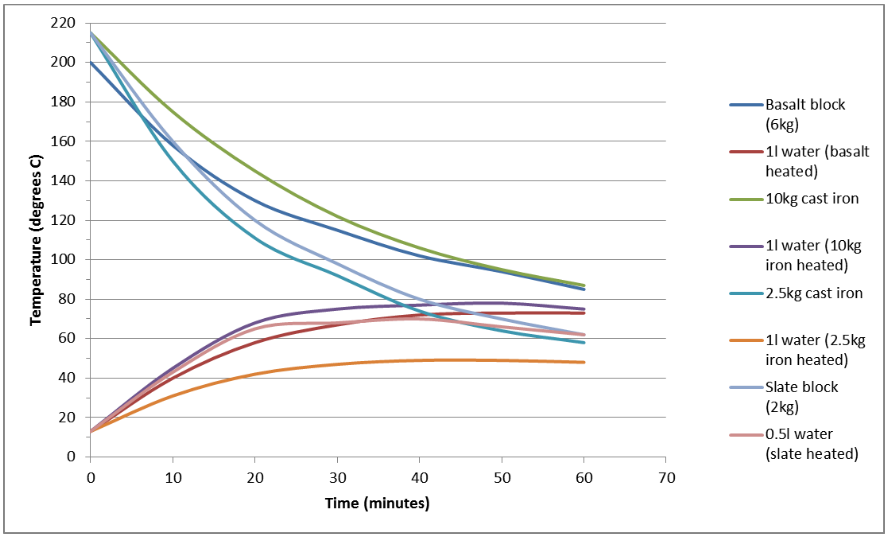
7.4

7.5 Efficacy of plywood sheet reflector and commercial 1.5m solar cooker to heat thermal storage loads (cast iron)



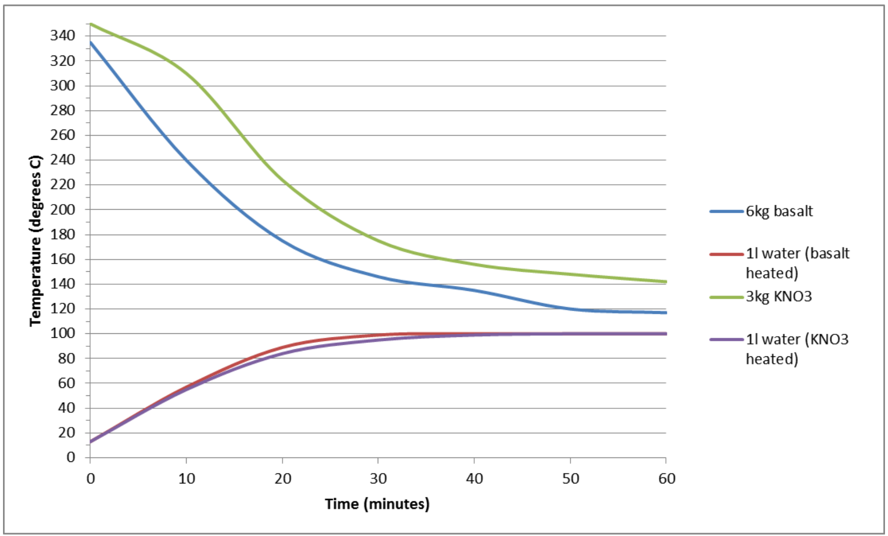
7.6

7.7 Paragraph 3.23 – efficacy of thermal storage materials to transfer heat for cooking (from 200 degrees)



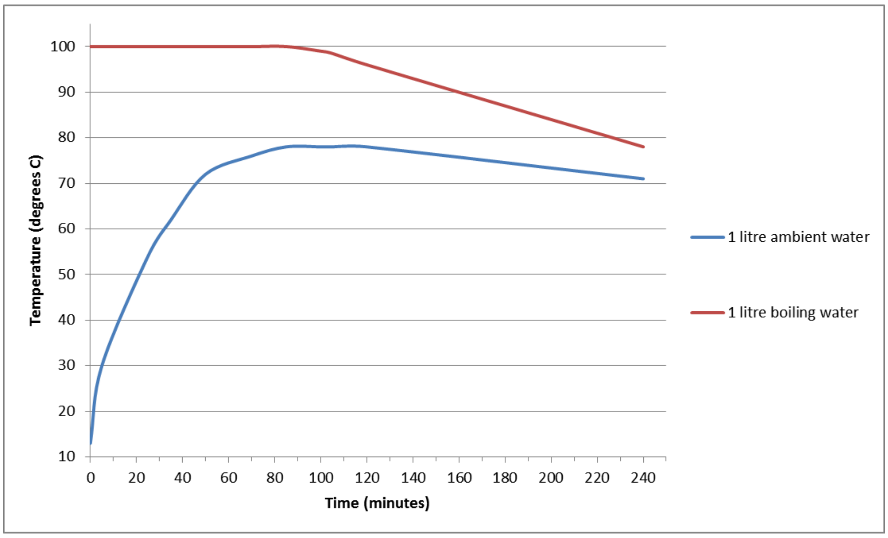
7.8

7.9 Performance of 6kg basalt vs 3kg phase change material at >300 degree to boil water



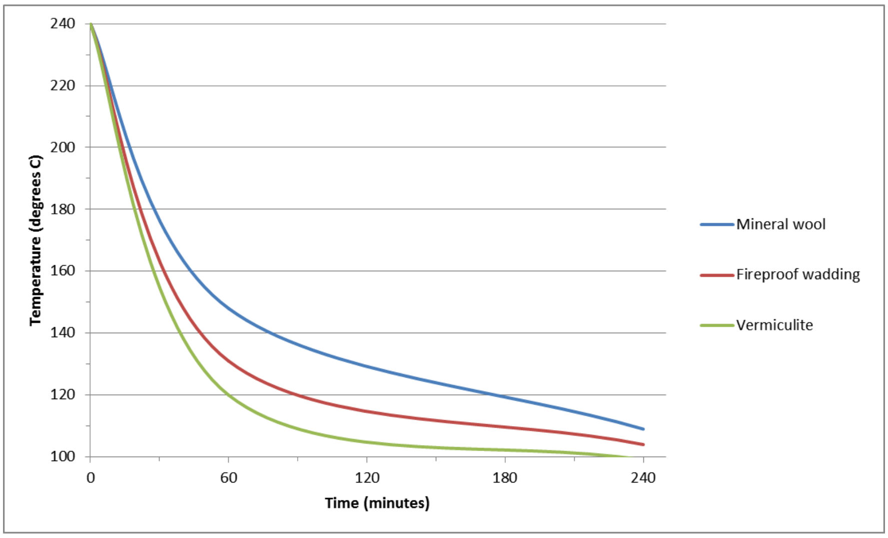
7.10

7.11 Performance of 12kg basalt at 215 degree at heating water vs maintaining boiling temperature



7.12

7.13 Paragraph 3.29 – performance of different insulating materials in retaining heat in thermal storage media



7.14

8. Appendix B – Cost assumptions

8.1 Parabolic reflectors

8.2 3.16.2 costings: Each parabolic reflector cooker can be constructed from 1-1.2m2 of sheet material, whether plastic or cardboard. Our assumption is that this material would be available in-country, if not for free, for <$1. This needs to be covered with aluminium foil. Bulk prices are almost certainly lower, but a 10m roll can be purchased for <$2, enough for 2 such reflectors. We used (imported) commercial wallpaper paste in our experiments. This, or thinned PVA glue, could be locally sourced, and the amount used on a single reflector would cost <$1. Similar, the cloth tape used to secure the panels in their shape – at $5 for 20m – would have a value <1$ for a single cooker. The 5 components at <=$1 each therefore make up the cost of <$5

8.3 The cost of a 2.4x1.2m sheet of plywood in Africa was $9. A roll of aluminium foil at $2, glue at <$1 and nylon rope fixings at $1 give the aggregated cost of $13, or £10.

8.4 3.57.1 costings: Cement retails in Africa for c $10 for a 50kg sack. A 10kg block of concrete could therefore be cast for $5 including embedded handles. Local pumice costs very little (<$1) but together with a suitable made-to-measure container might cost $10. If a large Fresnel lens were to be available costing $100, a suitable metal or wooden mounting frame, to keep it rigid and to move it appropriately as the sun moved, should be possible for under $20, giving a total system cost of $150 including a 10% profit margin.

8.5 3.57.2 costings: Following the above estimates, an insulated thermal storage element should be possible to make at a cost of under $15. For rigidity, a higher grade of plywood than we used in our tests would be necessary, probably 9mm. The cost of a sheet of this material in Africa is just under $30. The secondary reflector would need to be much more precise, albeit small. Although we did not experiment with this, let us assume the cost of a small parabolic satellite dish in Africa is $40. We believe, from our experiments, that a reasonably heavy-duty metal frame would be necessary to perform the three-fold duty of holding the plywood sheet in shape, maintaining the secondary mirror at a precise position with respect to the primary, and to allow the whole rig to move to follow the sun, whilst maintaining the focus on the thermal storage element. We do not know the cost of manufacturing such a rig locally, but for the purposes of this costing estimate, since it needs to be much stronger and more complex than the frame used in para 8.4 have based it at $90. This gives an aggregate system cost of $175, giving us the figure of $200 including a small profit margin.

8.6 3.60 costings: We assume that a site operator, with multiple devices, achieves certain efficiency of scale and can therefore source or construct systems at a 25% discount to the above system costings. This gives a per unit capital outlay of $130 or GBP100 or Tsh300,000.

8.7 If we further assume that the operator can charge 2 thermal units per device on each of 250 days of the year (we will assume that the other days will have insufficient sun – in fact the true situation is likely to be more complex, with some days yielding none, and some having enough sun for a single charge). This gives 500 charges per device per year. At TSh 200 (7p) a charge, this yields annual revenue of Tsh100,000 per device, or enough over 3 years to repay the capital outlay.

8.8 Integrating this into a larger business model, gives the following results. These figures are for a 50 device site, allowing 100 cooking processes per day (eg 50 families lunch & dinner). The assumption is that the entrepreneur is community member, so customer acquisition costs are zero. Microfinance is not widely available in the Simanjiro region – it is more usual for budding entrepreneurs to sell assets to raise capital (usually cattle). So this model similarly does not contain any interest payments (though we have run a parallel set of figures with 20% interest). From what we were able to see, entrepreneurs in the Simanjiro region do not generally plan in a salary or profit for themselves. After capital outlay, they take occasional amounts of cash out of the businesses as required and available, but nothing regular or planned. Nevertheless, we shall model for an annual "income" of $650. Maintenance will be done by the operator, since the systems are largely operator constructed. The only annual maintenance costs will be for material (foil, etc) and welding services.

8.9

8.10		no interest	20% interest
8.11	Income/yr:	TSh 5,000,000	TSh 6,125,000 (245TSh/day)
8.12	Costs /yr:		
8.13	Maintenance:	TSh 100,000	TSh 100,000
8.14	Operator profit/pay:	TSh 1,500,000	TSh 1,500,000
8.14.1	Interest/yr:		TSh 2,000,000 (averaged)
8.15	Profit/device/yr:	TSh 2,600,000	TSh 2,525,000
8.16	Capital costs:	TSh15,000,000	TSh15,000,000
8.17	Repayment period:	6 years	6 years

8.18 Therefore if the operator withdraws funds of $650 from the business every year in remuneration, they repay their capital outlay in 6 years at a customer price of TSh200 per thermal charge. If they were to borrow at 20% (and if that were available over more than 2 years, which is highly unlikely) it would be necessary to charge customers TSh245 to be able to repay capital and interest in 6 years. A customer unit cost of TSh 460 would be necessary to repay a load over 2 years at 20%. We believe customers are reasonably unlikely to pay such a high amount unless there is no alternative, however further research will investigate customer willingness to pay for thermal cooking services such as this.

8.19 4.4 costings: using a pyrolyser to generate the charging heat takes the capital investment for the reflector out of the equation. The above estimates show a thermal module should have a capital cost of under $15. At a capital cost 1/10th the amount of the systems discussed above, payback would be under 1 year even with a unit customer price of TSh100 (3p).

8.20 4.5 costings: using a minigrid to charge a device using spare power (at a discounted marginal rate of 5c/kWh) would use 700-800Wh of electricity per charge, which added to a customer rate of rental reflecting the capex and opex of a unit of 3c a charge, gives a price of 6.5c per charge, or 5p