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Adaptive design of a prototype electricity-producing biomass cooking stove

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ABSTRACT

This work is a second iteration of an adaptive design project aimed at developing an appropriate off-grid technology for small-scale electricity generation in rural Malawi, and possibly for other developing countries. Stakeholder and user feedback gathered from the initial technology demonstrator field trial has been used to inform design improvements of a re-engineered technology demonstrator which has subsequently been deployed in a different region of Malawi to assess its viability, robustness and appropriateness. The ultimate aim of the project is to develop a domestic electricity generator that can provide adequate, affordable and reliable electricity for charging low-powered electrical appliances such as mobile phones, LED lanterns and radios. The technology under development is a thermoelectric generator that is powered from the heat produced by biomass-fed cooking stoves. The re-engineered generator utilises a single thermoelectric generator (TEG) to produce up to 4 W of electrical power whilst using significantly less expensive and more robust components than the first demonstrator. Ten generators were fitted to a low cost and locally manufactured clay cooking stoves and then deployed in the predominantly rural Ntcheu district. The TEG-stoves were equipped with sensors and data loggers and remained in the field for up to 6 months. The users were able to charge their mobile phones, LED lanterns and radios from the stove. None of the stoves were used every day, indicating that the users operated other stoves or cooking methods based on preference. The data obtained showed a maximum power consumption of around 4.5 W · h of energy per day, which represents a 50% increase compared to the previous field trial. The user operation of the stove generator and user behaviour has exposed unexpected, yet fixable, issues with the battery discharge protection of the charge control circuit design of the initial technology demonstrator.

Introduction

Over 2.4 billion people worldwide use solid biomass fuels for household cooking and heating in open fires and basic stoves (MacCarty and Bryden, 2015). Improved cooking stoves have been identified as an encouraging alternative to traditional open fire cooking methods, and can offer many benefits such as improved fuel efficiency, personal risk reduction, indoor air quality improvements and a range of associated positive health impacts (Ruiz-Mercado et al., 2011). Whilst there are many factors influencing the adoption of any stove design (Pine et al., 2011), the addition of an electrical generator to an improved stove could make it more attractive than the traditional cooking methods whilst simultaneously tackling the energy access problem typically encountered by the very people using these stoves.

Electricity and other energy access are hugely important factors in establishing economic and social development on both a domestic and industrial scale (Winkler et al., 2011), yet affordable access to electricity remains one of the primary objectives of developing countries. Of the estimated 1.4 billion people lacking access, over 85% live in developing countries. Africa has the lowest electrification rate in the world (Adkins et al., 2012). The energy access problem is particularly problematic in sub-Saharan Africa (SSA), with the population having the least access to electricity compared to emerging countries from other regions (Onyeji et al., 2012).

It is not uncommon for off-grid rural villagers in developing countries to travel long distances by foot or bicycle in order to charge their mobile phones and other battery-powered devices. For many people a trip to the local charging station takes place more than once per week. For mobile phone charging, Manchester and Swan (2013) report an average fee of $0.20 per mobile phone charge. A survey study by Adkins et al. (2012) on rural household energy consumption in almost 3000 households in SSA found that the average household spent $58 on fuels and $19 on batteries per annum. Of these outgoings, $21 was spent on cooking-related purchases and $48 was used on lighting and electricity related purchases.

These types of expenditures represent a significant financial burden for many families in the developing world. If an electrical generator could be developed at an affordable cost which was capable of providing

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a small but reliable source of electricity at the household level, it would remove the need to pay for charging thus enabling people to focus their spending on other important areas such as nutrition, health and education. Integrating a generator with a cooking stove will allow the user to generate power during normal cooking practises. Furthermore, the ability to charge phones in their own homes means that users do not have to switch off their phones to conserve power (Manchester and Swan, 2013) and can therefore remain connected more often.

There is limited published research on the topic of integrating TEGs with cooking stoves, particularly those intended for developing countries. Typically, studies involve the investigation of the output power generated by stoves with integrated TEGs in a laboratory setting, such as studies (Eakburanawat et al., 2003; Lertsatitthanakorn, 2007; Nuwayhid and Hamade, 2005; Nuwayhid et al., 2003; Rinalde et al., 2010).

Raman et al. (2014) recently developed a forced draft combustion cooking stove in which a blower was powered by a thermoelectric generator. The blower removed heat from the cold side of the thermoelectric module, resulting in warmer air of 25 ~ 30 °C which was then supplied both below and to the top of the combustion chamber to obtain cleaner combustion and higher efficiency. At a temperature difference of 240 °C the generator was capable of producing 4.5 W, of which only 0.83 W was used to power the blower. The remaining power was available for mobile phone charging and LED lighting. The authors claim an efficiency improvement of ~ 16% compared to the improved cook stoves which operate on natural convection.

Similar work was conducted by Sawyer et al. (2008) who coupled a Taihuaxing TEP-1264-1.5 thermoelectric module with a Haitian cooking stove. The minimum requirement of the generator was to power its own cooling fan, although auxiliary component charging was also planned. The cooling air used to maintain the TEG cold side temperature was also used to increase efficiency of the stove by rerouting it to the combustion chamber. The chosen TEG was capable of producing up to 4 W at a temperature difference of 200 °C, but in practise this temperature difference could not be achieved due to rising cold side temperatures, since the design relied on the fan running at the maximum flow rate at all times

Of those researchers who field tested their designs, Killander and Bass (1996) were one of the first. Using two Hi–Z HZ20 TEG modules mounted on a 270 mm × 100 mm aluminium heat collector plate that was placed on the outside of a large wood-fed stove, they were able to obtain a maximum of about 10 W during the cold mornings, falling to 4–5 W in the afternoon as the house heated up. The output power was used to power the cooling mechanism and to charge four 6 V lead acid Exide batteries, which were in turn used to power a television at 12 V.

Mastbergen (2008) and Mastbergen et al. (2005) developed and field tested a TEG-stove generator system comprising two 14.7 W output TEGs and a fan-cooled aluminium heat sink with the objective of generating 45 W · h of electrical energy to provide enough power for lighting and some television. The target energy production was 15 W · h per meal assuming 3 meals per day. A 3000 cycle durability test was also performed to investigate the effects of operating temperature, module quality, and thermal interface quality on generator reliability, lifetime and cost effectiveness. The authors noted that the design was optimised for a very specific temperature range which was not consistently achieved by all users. It was discovered that the thermal resistance between the generator parts increased with thermal cycling because of a loosening of clamping bolts. Problems with the circuitry included excessive power consumption at low stove temperatures, and battery failure due to incomplete charging as users operated the lights and TV whilst the stove was in use.

Context of research and project objectives

There is little information in the literature regarding the true adoption of improved cooking stove programmes and how to sustain their long-term use (Ruiz-Mercado et al., 2011). There is even less published field data obtained from pilot programmes that seek to integrate electrical generators with the stoves. Furthermore, there still exists a gap in knowledge concerning the basic electrical power requirements of rural communities living in the developing world. Despite mobile phone and other battery powered devices becoming commonplace in even the most remote locations, little data is available in the literature to quantify how much electrical power users need to make a meaningful improvement to their lives. Much of the information gathered is, by necessity, in survey form such as that by Adkins et al. (2012).

Considering the above, the authors have initiated the adaptive design process for the development of the proposed TEG-stove technology. Adaptive design realises that one does not have full knowledge of the system and that the design must respond to the experiences of the users, shifting uncertainty and changes to goals and objectives that are part of the real world (Buckley, 2014). Adaptive design requires that feedback amongst researchers/designers, stakeholders and users/actors is an essential part of the process. This builds creative tension between the designers, stakeholders and actors such that the technology evolves iteratively towards an appropriate final design.

The initial phase of this adaptive design process involved the design, laboratory testing, and field trial testing of an electricity producing cooking stove (O'Shaughnessy et al. , 2014; O'Shaughnessy et al., 2013) along with the development of ancillary technologies such as charge control circuitry (Kinsella et al., 2014). Largely relying on modified commercially available technology to maximise electrical power production, generators were fitted to locally-made Malawian clay cooking stoves. In total, five generators were deployed to a rural village in the Balaka district of Malawi with the help of Concern Universal. In order to inform the adaptive design process, the stoves and generator systems were fitted with sensors and logging equipment that recorded relevant information every minute for 80 days. The empirical information gathered included, though was not limited to, the temperature within the stove i.e. when it was in use and when it was not, the power produced and stored in the supplied rechargeable battery and the power used when participants were charging devices. The main results which have informed this iteration of the design were:

1. The technology was used as intended and was valued by the participants
2. The time during which the cooking fires were lit was significantly higher than the estimate that informed the initial design
4. The energy produced was far in excess of what was actually used
5. The generator protruded too far from the side of the stove causing reliability issues
6. The generator system was not affordable

This research paper aims to discuss the results and provide conclusions associated with the second full iteration of this technology design. The intention is not only to explain the technology under development, but also to provide a real-life example of the adaptive design process being implemented for a new technology for the developing world.

TEG, battery and stove selection

Thermoelectric generators, or TEGs, are solid state energy devices which convert heat directly into electricity by means of the thermoelectric effect. For succinctness, a detailed explanation of thermoelectricity is not provided here. An excellent overview of thermoelectricity is given by Rowe (1978) and more recently by Hodes (2005). The model adopted in this study is described in detail in O'Shaughnessy et al. (2013) and Kinsella et al. (2014) and uses the 'Effective Seebeck Coefficient' method employed by Hsu et al. (2011), which calculates the Seebeck coefficient α under realistic conditions. The output electrical power of the generator is dependent on the internal resistance of the TEG, the temperature difference between its hot and cold faces and the resistance of the load, and can be obtained from Eq. (1).

$$P_{elec} = (\alpha_{eff}\Delta T)^2 \frac{R_L}{(R_L + R_{TEG})^2} \tag{1}$$

Theoretically, maximum power is obtained when the TEG resistance matches the load resistance; i.e. when $R_{TEG} = R_L$. As an example, the chosen TEG1-12610-5.1 supplied by Thermal Electronics Corp., Ontario, Canada, can supply up to 8 W at a matched load output voltage of 4.2 V with hot and cold face temperatures of 275 °C and 30 °C respectively. This TEG also has a graphite layer on both sides to reduce thermal contact resistance and increase heat flow through the module.

The TEG is used as a power source to charge a rechargeable lithium–iron–phosphate ($LiFePo_4$) battery, specifically the ANR26650 cylindrical cell manufactured by A123 Systems. $LiFePo_4$ batteries are known for their good safety characteristics and long life cycles. Some battery specifications are provided in Table 1.

In this study, the term generator refers to the complete assembly of the heat collection, TEG module and heat dissipation components. The generator is retrofitted to a clay cooking stove named the 'chitetezo mbaula'. It is a portable, though heavy (~12 kg) stove which is made by women's groups in Malawi and is marketed as a cleaner, safer and more fuel efficient alternative to the traditional 'three stone fire' cooking method (Malakini et al., 2014). This stove is becoming more prevalent throughout the country since the government's commitment to 2 million clean cookstoves by 2020 (Embassy of the United States Lilongwe Malawi, 2014).

Heat sink selection

To maximise power from the TEG, the temperature difference between the hot and cold faces should be maximised without exceeding the upper temperature limit. It is desirable to maintain the cold side of the TEG at the lowest temperature possible to achieve maximum power. Active cooling methods such as fan-assisted air blowing or liquid pumping require electrical power to function. Since the TEG in this study produces a maximum of 4 ~ 6 W of power when integrated with a cooking stove under normal operation (O'Shaughnessy et al., 2014), it is desirable to keep parasitic power drains to a minimum. Previous studies by the current authors employed a relatively expensive heat pipe CPU heat sink to aid cooling of the TEG (O'Shaughnessy et al., 2013, 2014), which was capable of maintaining the cold side of the TEG at 70 ~ 80 °C under real life conditions in a stove operated by the intended users. The initial field trial determined that the in-use energy generation was about 9 W · h per day with users consuming a third of this (O'Shaughnessy et al., 2013, 2014). This design, although effective to the point of energy overproduction, was prone to a mechanical failure due its cantilevered profile from the edge of the stove. Furthermore, the complexity of the assembly and integration of the generator with the stove meant that installing the system was a cumbersome and time consuming task. This was not so apparent during laboratory testing in Ireland, but became obvious once a small batch of generators had to be produced in a short time frame in Malawi. These issues, along with the fact that the high performance heat sink system was a substantial portion of the component cost of the generator, indicate that the first redesign should incorporate a slim, low-cost and reliable heat sink.

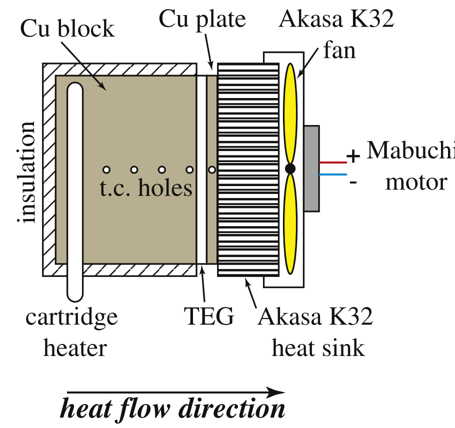

Fig. 1. Laboratory-based experimental rig.

Several experiments were performed in the laboratory to ascertain the cooling effectiveness of different heat sink/fan combinations. A sketch of the experimental apparatus is shown in Fig. 1. The simple rig consists of a single TEG1-12610-5.1 module maintained between a copper block and plate. The block is heated by an imbedded cartridge heater. Thermocouples located in the block and plate at known positions allow the estimation of the heat flux supplied to the hot side of the TEG, and the approximation of the temperature difference across the module. The rig was designed so that any heat sink could be fitted to the cold side copper plate. For each heat sink tested, the cooling performance using the original fan/motor supplied with the heat sink was investigated before changing to a modified fan driven by a low power consumption DC motor. The cartridge heater was supplied by a variable AC power supply and monitored using two Fluke 117 multimeters. Power to the 12 V fan/motor assemblies was supplied with an Aim-TTi EX2020R desktop power supply. For all modified fan tests, power was supplied by the TEG and accompanying circuit almost identical to that described in O'Shaughnessy et al. (2014).

The heat sinks were ranked based on cooling effectiveness, cost, complexity and ease of assembly and integration with the stove. The selected heat sink was the Akasa K32, a commercially available heat sink normally used in CPU cooling. This heat sink is significantly lower in price and weight and has a slimmer profile than the previous design. Some manufacturer's specifications for the Akasa K32 are provided in Table 2.

The 92 mm diameter fan supplied with this heat sink is designed to operate at 12 V and consumes up to 2.3 W of power at its rated voltage which is almost 60% of the maximum power that the chosen TEG can produce when the cold side is kept at the anticipated value of 80 °C. Instead, and similar to the method adopted in O'Shaughnessy et al. (2013, 2014), the impeller from this fan is dismantled from its motor and connected to the spindle of a low power Mabuchi RF-500 TB-14415 DC motor which can run the fan from much lower voltages (~0.3 V). The fan and motor typically consume up to 0.5 W in total

Table 1
$LiFePo_4$ battery specifications.

Cell dimensions (mm)	ϕ 26 × 65
Cell capacity, nominal/minimum (Ah)	2.3/2.2
Voltage, nominal (V)	3.3
Max. continuous discharge (A)	70
Operating temperature (°C)	−30 ~ 55
Typical cycle life	>1000

Table 2
Akasa K32 manufacturer's specifications.

Cooler dimension	94.8 × 94.8 × 62.3 mm
Heat sink material	Aluminium fins
Heat sink core material	Copper core
Mass	326 g
Fan dimension	∅92 × 25 mm
Max airflow	56.81 CFM
Voltage rating	12 V DC
Fan life expectancy	40,000 h

when used with this TEG and circuit. Furthermore, since the fan is connected in parallel with the TEG, its supply voltage is directly linked to the TEG. This means that the fan rpm will increase as the TEG output voltage increases, i.e. when the temperature difference across the TEG increases.

Modifying the fan reduces its cooling capacity somewhat, but adequate cooling can still be achieved as shown in Fig. 2, which plots the data obtained from an experiment with the Akasa K32 heat sink and modified fan. The selected TEG can withstand intermittent excursions to 300 °C but for continuous operation a temperature of 280 °C is not to be exceeded. The graph shows that up to 4.4 W of power was generated by the TEG. At the highest heat throughput the TEG hot side temperature rose to 280 °C. The corresponding cold side temperature was maintained at 88 °C, which is about 15 °C higher than the previous design. During these experiments, a maximum of 0.43 W was used for cooling.

Since the Akasa K32 does not have embedded heat pipes it was expected that cooling performance would be reduced compared with the Arctic Cooling Freezer 13 employed in the previous design. Thus, the rise in cold side temperature is not surprising. For TEGs, power output is proportional to the square of the temperature difference. Fig. 3 provides a comparison of the two generators when tested using the same apparatus and circuitry. Clearly, at larger temperature differences the version 1 generator provides more power. This is due to the lower cold side temperatures. Even at the same temperature difference, the TEG with the lower cold side temperature will typically generate a higher voltage.

As mentioned, results from the first field trial indicated an oversupply of electrical energy, with users demanding approximately 3 W · h per day on average (O'Shaughnessy et al., 2014). However, if the current design reduces cost, complexity and ease of assembly and integration whilst increasing robustness and still meeting the electricity demand, then the lower power output should be acceptable.

Generator design, assembly and integration

To instal the generator, a hole is made in the side wall of the stove. Before this, a fire is made in the stove to check for cracks or stress during thermal expansion. The handles of the stove remain intact to ensure portability. The generator is assembled and installed as a single unit. The thickness of the walls is such that removing a small section does not markedly weaken the stove. In the future, the generator hole will be prefabricated during the manufacture of the stove.

The TEG is located between two 50 × 50 mm copper plates. Calibrated K-type thermocouples are inserted into these plates to estimate the temperature difference across the module. On the hot side of the TEG three copper rods protrude out of the copper plate into the combustion chamber. The rods deliver heat to the TEG, but are primarily intended to be used as a fire grate to aid combustion by allowing air to be drawn into the stove beneath and upwards through the fuel. The field trial participants were also encouraged to use a stick rest when operating the stove so that the sticks could be placed across the copper rods.

A thin sheet-metal skirt is placed on the inside of the stove. The sheet serves several purposes by preventing some heat from escaping to the walls of the stove, and also by reflecting this heat back to the centre of the combustion chamber. It also protects the TEG from direct exposure to the fire.

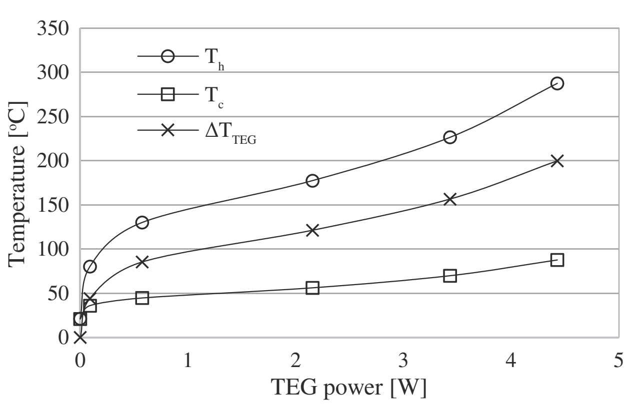

Fig. 2. TEG temperatures vs output power using the Akasa K32 heat sink and modified fan.

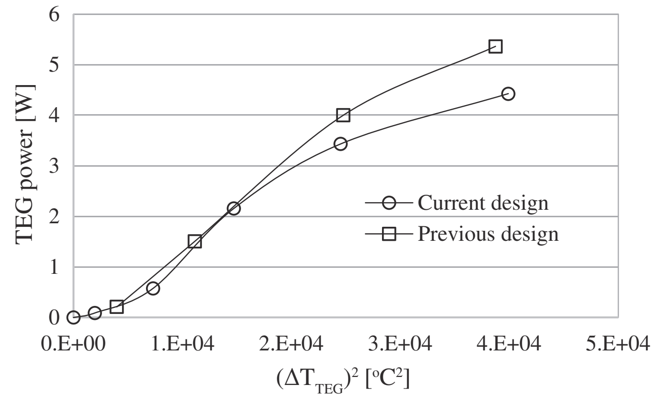

Fig. 3. Comparison of the previous and current cooling methods using the same test apparatus.

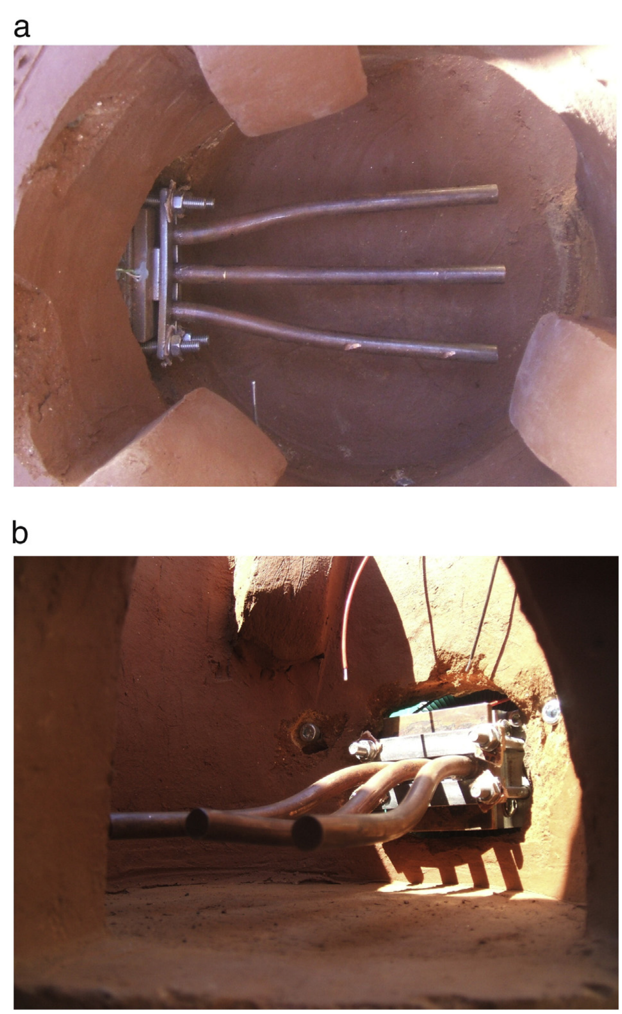

Fig. 4. Heat collection method showing the copper rods acting as a grate.

A photograph of the generator integration with the stove is provided in Figs. 4 and 5. As shown in the images, a metal bar is used to mount the generator to the stove. This bar is also connected to a small metal plate. This method is used to reduce the bowing effect observed during the previous field trial which led to loosening of the clamping bolts and a pressure reduction on the TEG module.

Battery charging circuitry

The power generated by the TEG is primarily used to charge a 3.3 V lithium iron phosphate ($LiFePO_4$) battery, termed the 'primary' battery henceforth. The circuitry used to charge the lithium-iron-phosphate battery is designed to be as simple as possible. Previous studies using this basic circuit have shown that the system approaches the maximum power point when the temperature difference across the TEG is close to or above 150 °C (Kinsella et al., 2014; O'Shaughnessy et al., 2014). Sophisticated maximum-power-point-tracking (MPPT) techniques such as those investigated in Ko Ko et al. (2011), Montecucco and Knox (2015), Sungkyu et al. (2010), and Xiaodong et al. (2010) were not employed.

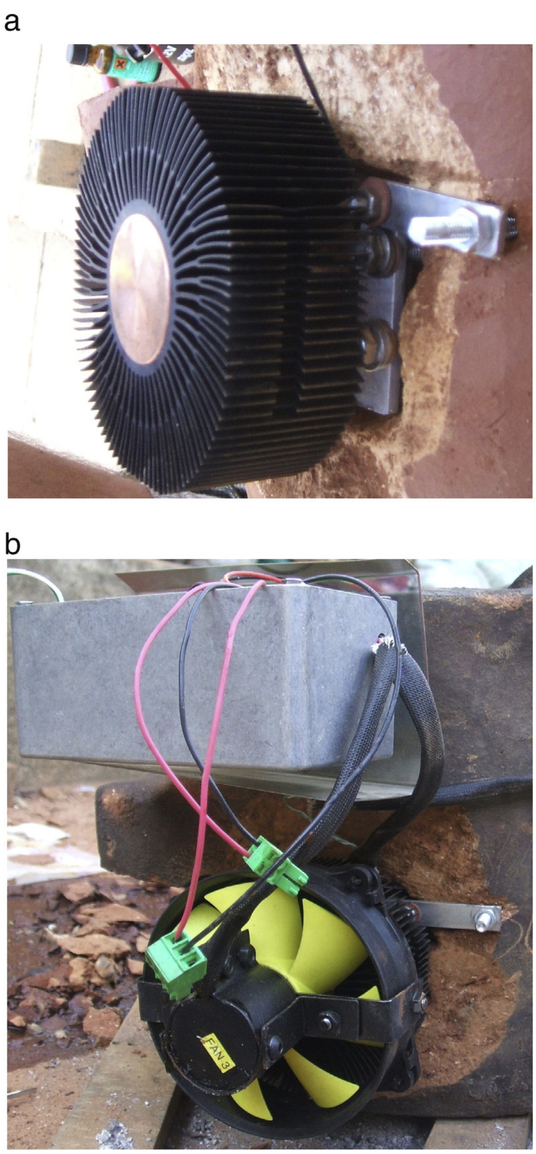

Fig. 5. Mounting of the generator's heat sink and circuit box to the stove wall.

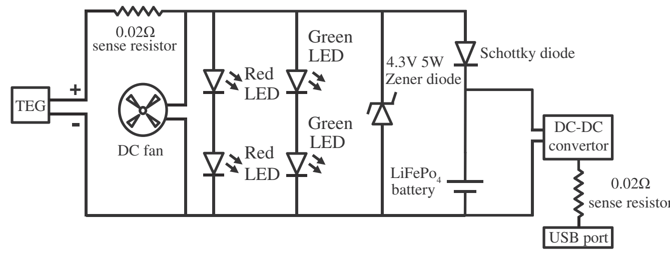

Fig. 6. Primary battery charging circuit.

A circuit diagram is provided in Fig. 6. The circuit includes the following features:

1. 0.02 Ohm sense resistors enable the calculation of the current and power produced by the TEG and consumed through the USB port by measurement of the voltage drop across the resistor.
2. A Schottky diode prevents the battery from discharging to the TEG. The Schottky diode has a small voltage drop across it, and consumes up to 0.4 W at full TEG power.
3. A 4.3 V Zener diode prevents battery overcharge by bypassing the battery when the battery nears full charge. Previous versions employed a 3.9 V Zener diode which leaked current from voltages as low as 3 V. The new diode reduces this power loss.
4. A pair of red LEDs indicate when the TEG voltage is sufficient to charge the battery.
5. A pair of green LEDs indicate full charge.
6. A DC–DC converter boosts the output voltage to a more useful 5 V, and is connected to a male USB port.

Results and discussions

In total, ten TEG-stoves were manufactured and then deployed in rural communities in Malawi: five to the participants in Kalata Village, Ntcheu, and five to participants in James' Village, Ntcheu. Concern Universal field facilitators trained the recipients in TEG-stove usage. Every participant was provided with a rechargeable battery-powered SunKing LED lantern as described in O'Shaughnessy et al. (2013). Each generator stove was equipped with a MadgeTech Quadtemp 4-channel thermocouple data logger which recorded the temperature in the stove wall, combustion chamber (i.e. in the fire), and the approximate temperature on either side of the TEG. A MadgeTech Volt101-A data logger enabled measurement and subsequent calculation of the current drawn via the USB by recording the voltage drop across a 0.02 Ohm sense resistor. All data loggers recorded for the entire duration of the trial at the selected recording rate of one reading per minute. All ten stoves remained logging in the field for up to 6 months or until the point of failure. Users were instructed that electricity would be generated as a by-product of normal stove operation, and that there was no need to burn more fuel or for longer periods. If desired, the LED lantern could be recharged during the daily cooking practises.

Pre-deployment testing in Malawi

Since the generators were expected to produce less electricity in Malawi due to the higher ambient temperature, increased sunlight exposure and also due to user behaviour, the TEG-stoves were submitted to a series of trial burns prior to field deployment to verify that all generators operated to a comparable level. Fig. 7 shows that all stoves produced a similar power output of approximately 4 W. Although the TEG voltage was not directly measured in the trial the maximum obtainable TEG voltage for this design can be estimated once the apparent temperature difference is known by applying a curve-fit expression obtained from these graphs. Note that TEGs typically display a hysteresis effect, meaning that the heat up and cool down profiles are slightly different.

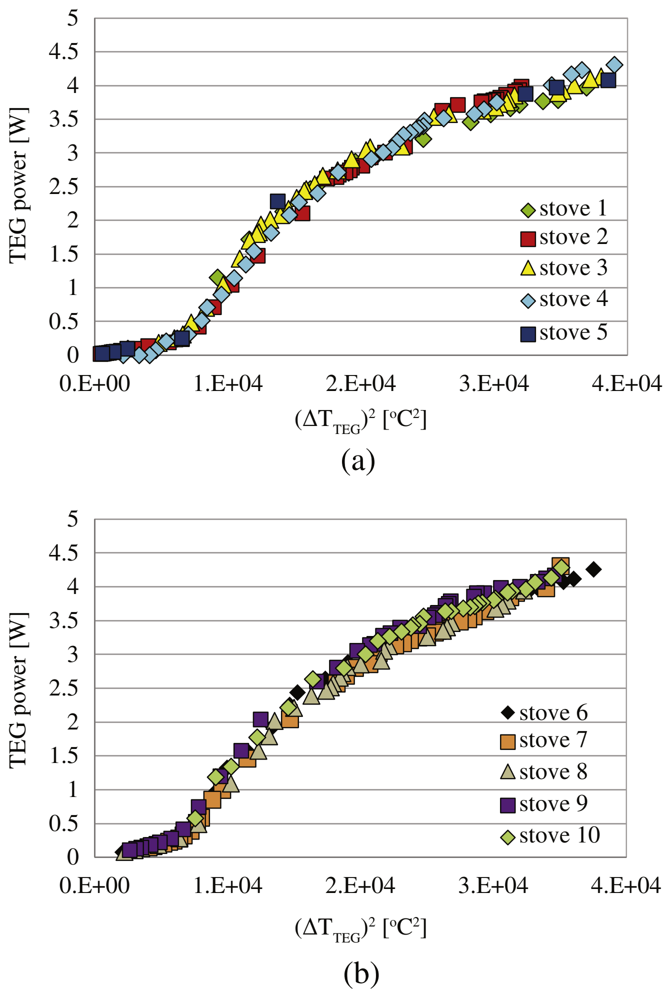

Fig. 7. Pre-deployment testing of all TEG-stoves.

Field trial TEG-stove usage

There appears to be little factual data concerning user behaviour for traditional or improved cooking stoves. By necessity, much of the information is gathered in survey or questionnaire form. The difference between the verbal answer and measured data can often be vast. This was especially noticeable during the first field trial when one participant stated that he used his stove several times every day, yet the data loggers showed frequent gaps lasting several days. By datalogging each TEG-stove in this study it is possible to ascertain reliable information regarding how often the participants operate their stoves. This is of course crucial in the design of this technology since energy is produced when the stoves are in use.

The term 'usage time' is defined in accordance with the method adopted in O'Shaughnessy et al. (2014). Since visual observation was not possible, a threshold value of 100 °C is chosen. Only when the temperature recorded by the combustion chamber thermocouple is above this value is the stove deemed to be in use. It is not known if the user is actively tending to the stove however, and therefore the usage time will include some periods of idleness or cool down. It is noted however that the temperature in the combustion chamber at the thermocouple location drops very quickly if fuel is not being burned.

It was concluded from the data recorded during the first field trial that prolonged stove usage was not uncommon and not solely attributable to the inclusion of the TEG generator since it was observed in the control group as well (O'Shaughnessy et al., 2014). Similar behaviour was determined during this study. Fig. 8 plots the average and

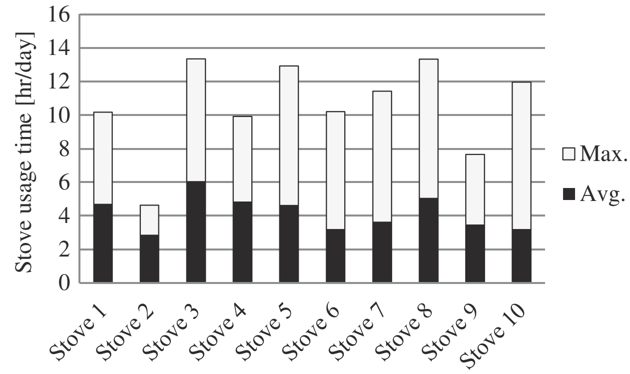

Fig. 8. Stove usage during trial.

maximum daily stove usage for all TEG-stoves. Only those days when the stove is operated are taken into account in the average. The figure shows that on those days when the TEG-stoves were operated, all participants used their TEG-stoves for 3 hours or more, with the highest average of 6 hours. Maximum daily usage time exceeded 10 hours for 8 of the stoves.

Since the average values in Fig. 8 only take into account those days when the TEG-stove is operated, it does not offer insight into the frequency of TEG-stove use. The data obtained shows consistency neither in the number of burning periods per day, nor in the total time spent cooking per day. TEG-stove user behaviour is erratic and varies day to day. Ideally, the TEG-stove would be used as the sole cooking stove so that electricity could be produced as a by-product of normal cooking routines. To analyse the frequency of use Fig. 9 plots the number of zero-usage days during the first 30 days of the field trial. Apart from TEG-stove 2 which was broken by the user almost immediately, none of the participants used their TEG-stove every day. The plot indicates that the TEG-stoves were used infrequently, possibly because of problems with electricity production or perhaps because of the presence of a second stove. There may be other reasons for this; e.g. lack of food to prepare or a desire to preserve the TEG by only using it at selected times stove. Where possible, later studies will also investigate differences in stove usage based on agriculture or climatic calendars to see changes in usage patterns.

- Field visits to the participant households indicate that many users have more than one cooking stove. This is in accordance with results described by Ruiz-Mercado et al. (2011) who found that when a new stove is brought into a household, the household members frequently stack stoves and fuels and select a device that best fits the particular cooking practise.

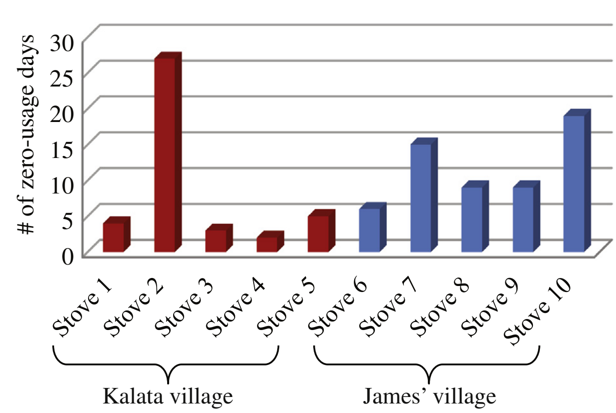

Fig. 9. Zero-usage days during first month.

Power consumption behaviour

Concern Universal field facilitators selected the villages for participation in the trial. Fig. 9 highlights differences in stove usage between the two villages. Whilst every recipient of a TEG-stove could potentially charge their neighbours' mobile phones (and in doing so generate a small amount of income if desired), in Kalata and James' village the TEG-stoves were given to members of a stove producing group. This enabled the groups to use the generated electricity for rechargeable LED lighting which also enabled them to work at night and produce more stoves than otherwise. This may have encouraged those people to use their TEG-stove more often. Unfortunately it also created jealousy amongst the village members who were not part of the stove making group, who saw those women receiving the TEG-stoves as having a double advantage. Indeed in follow-up group discussions, income generation was mentioned as one of the most beneficial elements of the stove.

The behavioural differences between the two villages raise a salient point that must be addressed: does the inclusion of the TEG generator alter the normal stove usage behaviour? In particular, do the recipients of the TEG-stove use it primarily to generate electricity? Moreover, do the participants use it *only* to generate electricity and not as a cooking stove? Some criterion is necessary for establishing whether the TEG-stove user is charging an appliance. Since the power output consumed through the USB port was monitored during the trial this is the logical choice. A threshold value of 0.25 W is selected. This value is high enough to ignore the small current ripples produced by the DC-DC convertor but low enough to capture those moments when an appliance is being charged. Table 3 displays the different results based on the simultaneously recorded combustion chamber temperature and USB power measurements.

During the previous field trial the user of TEG-stove 3 operated her TEG-stove only when she needed electricity (O'Shaughnessy et al., 2014), and kept it hidden safely when not in use so as to protect what she deemed was a valuable asset. For the current study, it was anticipated that, due to the novelty and other factors, TEG-stove users would occasionally make a fire in the stove purely to generate electricity. Isolated examples of this behaviour undoubtedly occurred. However, if this trend was generally true one would expect that the user would minimise the time spent burning fuel in the stove without a connected appliance. Fig. 10 shows that this is not the case. For most of the TEG-stoves the time spent generating power (i.e. burning fuel in the stove) without a connected device was in excess of the time spent generating whilst outputting power to a device.

The 'Generating not Outputting' data in Fig. 10 highlights that many users operate the stove for intervals without providing power to an appliance. Whilst we may reasonably conclude that some cooking was carried out with the TEG-stoves, the 'Generating not Outputting' data also incorporates those periods where the following might be true:

1. Appliance is connected but insufficient power is available for output to the appliance (i.e. during stove start-up or cool down).
2. Appliance is disconnected after charging and the fire in the stove is left to burn out.
3. Stove is fired for other purposes (some background light, space heating).

By analysing the output power profiles it is also observed that the users preferred to connect their devices whilst the stove was in use

Table 3
Criteria for establishing if and when power is output from the circuit to an appliance.

$T_{chamber}$	P_{USB}	Result
>100 °C	<0.25 W	Generating not outputting
>100 °C	>0.25 W	Generating and outputting
<100 °C	>0.25 W	Outputting not generating
<100 °C	<0.25 W	Stove not in use

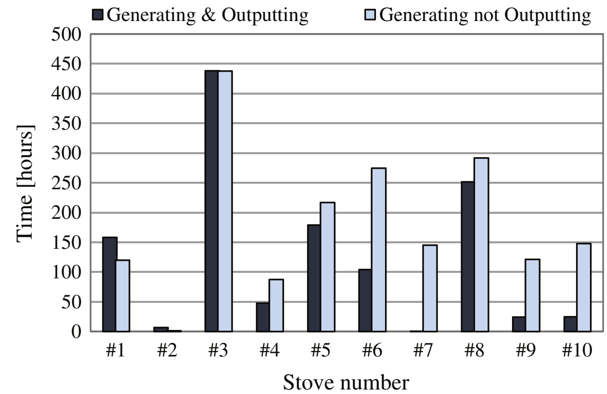

Fig. 10. User appliance charging behaviour during the trial.

rather than wait and use the energy stored in the battery, as shown in Fig. 11. Indeed, all users favoured this method. Such behaviour raises questions about the capacity and indeed the necessity of a rechargeable battery, especially such an expensive one.

Appliance charging

Fig. 12 plots a selected daily power consumption profile for one of the field participants. Also displayed in the figure is the apparent TEG temperature difference which gives an indication of the stove usage and maximum possible power generated. From the figure it is clear that there was no usage period until after midday, meaning that the user likely cooked breakfast using another method. There are two distinct appliance charging profiles before noon during which the energy stored in the battery is expended to charge the connected device. The first charge profile is typical of the SunKing LED lantern that was supplied with the TEG-stove. This lantern typically accepts a constant power of 2 ~ 2.2 W (O'Shaughnessy et al., 2013). The second charging instance is typical of mobile phones, comprising an initial peak in output power before dropping off as the phone battery increases in charge level. There follows a small spike in output power before noon. It is possible that the user connected a device to the circuit's USB port but had already depleted the primary battery when charging the mobile phone. This may explain the reason for starting a fire in the stove around 13:00, since a device is almost immediately connected. Conversely, the user may have planned to cook at this time regardless, and since there is a time gap between appliance connections, the user may have been motivated to use the TEG-stove for cooking over another method because it produces electricity. The charging profile during this period is indistinct and results from the user trying to charge a device whilst the circuit is attempting to recharge the primary battery. Another burning period begins around 19:00 during which no device is connected to the USB port.

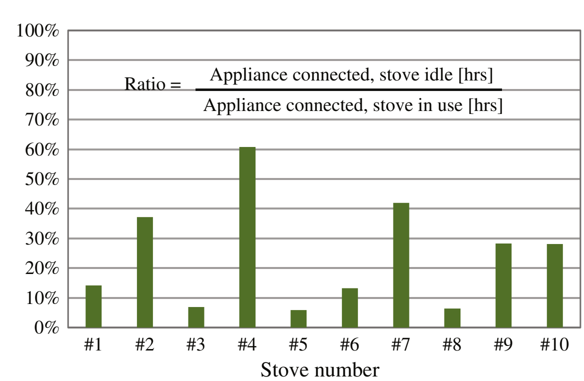

Fig. 11. Power output to devices when the stove is idle relative to when it is in use.

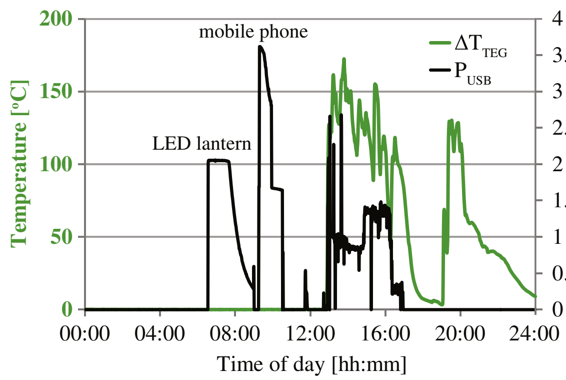

Fig. 12. Selected daily power consumption profile.

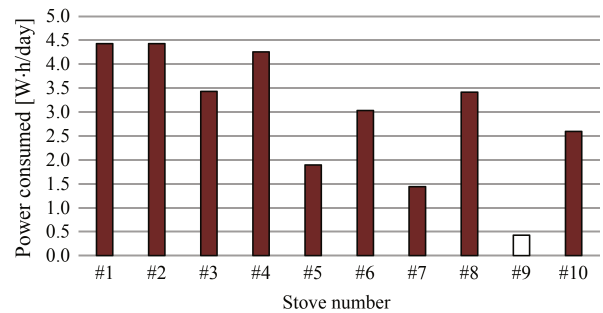

Fig. 13. Average daily power consumption.

From the field trial data, field visits and follow up surveys, it became clear that the users were able to recharge the provided SunKing LED lanterns as well as mobile phones and radios. 12 V batteries were present during field visits and many people asked if changes could be made to the generator design so that these batteries could be charged. One user commented that she started a small phone charging business and charged neighbours a smaller fee than they would pay in the local charging station. Another user stated that she would charge neighbours' phones for free provided they brought the firewood. This was done to ease tensions in Kalata village between the TEG-stove recipients (each one also a stove producer) and those without. In these instances, there could be a queue of several mobile phones waiting to be charged, which was not the intended operational design point for the generator. Nevertheless, it is an interesting outcome and useful information that will be incorporated into the next generator design iteration. It may also contribute to the commercial viability of the final design.

As mentioned previously, there is relatively little empirical data available on the power requirements of rural villagers in developing countries. Of course, the goal is frequently to provide as much power as possible, yet small quantities of electricity can have a significant impact. For example a fully charged SunKing lantern can provide up to 16 hours of light on a single day's charge (O'Shaughnessy et al., 2013). Manchester and Swan (Manchester and Swan, 2013) conducted an experimental study on the energy and power demands of mobile phone charging using an inverter powered by a 12 V car battery which is a charge configuration regularly encountered in developing countries. Their results showed that the average energy requirement per mobile phone charge using their method was 7 W · h (with less power likely delivered to the mobile phone battery), but this figure could reach 13 W · h depending on the inverter load. In SSA, daily phone charging is unlikely if people have to travel great distances and pay a nominal fee (Manchester and Swan, 2013). Results from the first Malawian field trial of the generator in this study indicated that users consumed approximately 3 W · h per day on average (O'Shaughnessy et al., 2014), though this figure relates to all electrical devices charged or powered, not just mobile phones. Indeed, field trial participants placed huge value on the rechargeable SunKing LED lanterns that were provided with the TEG-stoves. Even when the generators were collected for analysis or failed, these lights remained with the participants and were still charged in the local charging station for the price of a mobile phone charge, which was unexpected.

Using the second generator design iteration investigated in this study, the average power consumption differed for each user as evidenced by Fig. 13. The average in this plot takes into account every day to the end of the trial or until the point of failure. In accordance with Fig. 9 there is a difference between the two villages, with the users of TEG-stoves 1 to 5 consuming more power on average than the users of TEG-stoves 6 to 10. A maximum value of 4.5 W · h per day was obtained for TEG-stove 1. It is noted that some of the data logger files for TEG-stove 9 were corrupted which made accurate determination of the average impossible. As an example, TEG-stove 3 was used most frequently (140 of 180 days) and its user consumed 3.5 W · h per day. It is difficult to be certain if this value represents the daily requirement or merely what users were able to produce from the stove. Indeed there are many instances of appliances connected to the stove whilst it is in use but there is insufficient power to charge. The users may be restricted by generation capacity in this regard. However, since the option of burning more often to produce more electricity is available, it would appear from the graph that a value of 4.5 W · h per day is at least indicative of the daily power required to maintain the basic services of mobile phone charging and lighting. This represents a 50% increase compared to the previous field trial. Some of the users' approach to appliance charging was much more demanding of the circuit than in field trial 1, and this behaviour ultimately led to its failure as described in the following section.

TEG-stove failure analysis

The different usage times displayed in Fig. 10 indicate that some stoves may have failed early in the trial. By analysing the temperature profiles it is usually possible to determine the point, and possibly cause, of failure. The thermocouples located in the copper plates allow for an estimate of the apparent temperature difference across the TEG module (Kinsella et al., 2014). Fig. 14 plots the maximum TEG hot and cold side temperatures recorded during the trial. Also in the figures is the average of the daily maxima. Once again, only those days when the stove is operated are taken into account. For optimum performance from the TEG, the hot side should be maintained at approximately 270 ~ 280 °C with intermittent excursions above 300 °C permissible. Extended periods at higher temperatures result in TEG degradation and eventual failure (Mastbergen, 2008). Fig. 14 shows that the average daily maximum TEG hot side temperature was kept within the permissible range apart from stoves 1 and 3, which exceeded 300 °C. The maximum values for each stove were typically recorded after the generators had failed.

Following laboratory and pre-deployment testing in Malawi, it was anticipated that cold side temperatures would be maintained in the 80 ~ 95 °C range. The higher cold side TEG temperatures observed in Fig. 14b indicate that the cooling method was incapable of maintaining the target cold side temperature. Upon revisiting the households it was clear that the plastic fan casings had melted on some TEG-stoves. At the end of the trial all samples were returned to the laboratory for testing where it was determined that the fan and low power DC motors still worked as intended. Six of the ten thermoelectric modules were also still operating correctly. It was concluded that the problem was related to the power delivered to the fan and was not a mechanical issue.

When the user operates their TEG-stove without connecting a device, the generated power is used primarily to charge the $LiFePo_4$ battery. If the user connects a device to the TEG-stove during cooking, most of the power delivered to the device comes indirectly from the TEG and the energy is not stored in the battery. However, when the

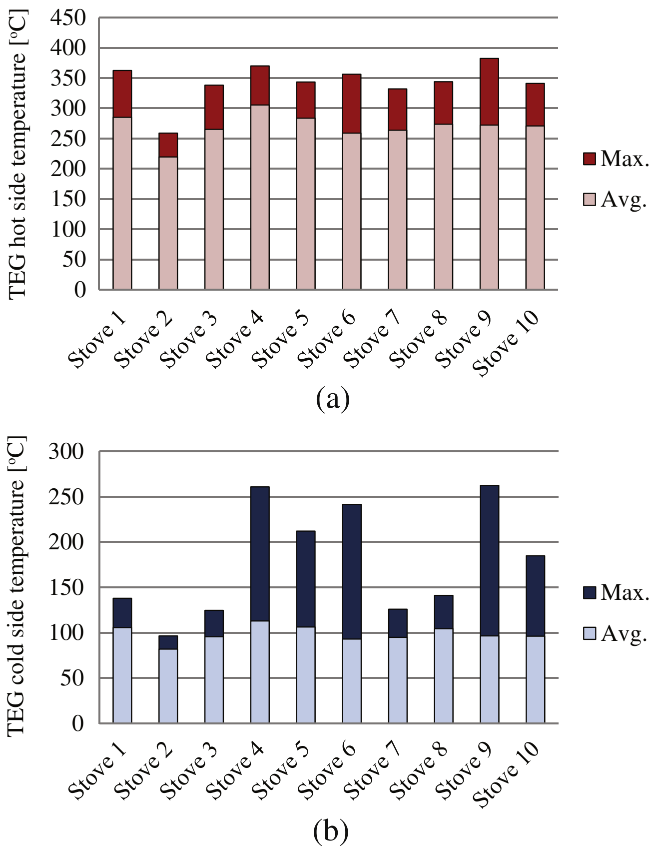

Fig. 14. TEG temperatures during trial.

user connects a device when the TEG-stove is not in use, the power comes from energy previously stored in the primary battery. As energy is drawn from the battery, its voltage drops.

To investigate the failure mode in further detail a small sample of stoves were fitted with an extra MadgeTech Volt101-A data-logger to monitor the primary battery voltage. A user-operated ON-OFF switch was also included between the DC-DC converter and the output and the participants were instructed to place the switch in the ON position when outputting power to an appliance, and in the OFF position when the appliance was disconnected. These stoves were subsequently redeployed into the field.

Fig. 15 plots the battery voltage for TEG-stove 7 over a 6-day period. The graph shows the battery voltage initially at the nominal and safe value of 3.3 V, with a slight drop off in voltage due to the DC-DC converter and minimal reverse leakage current through the diode. This indicates that the users were not operating the switch. At some point on the second day a device is connected. The battery discharges quickly and its voltage drops to 2.2 V after 0.6 hours of charging. The DC-DC convertor should stop boosting to 5 V when it sees an input voltage of less than 2.2 V but this appears not to be the case. When no device is connected to the generator some current leaks from the battery through the DC-DC converter and the battery voltage gradually reduces over time. The recommended cut-off voltage for this battery is 2 V and the recommended lower voltage limit is 1.6 V. The figure shows that the battery continued to discharge below the absolute limit of 0.5 V. This took place over a period of 2 days. Despite this, during the next burning period the battery was recharged by the TEG to almost 3 V before discharging once again. The discharging/recharging continued until the battery dropped to 0 V on day 6.

Fig. 15 shows that the battery could be recharged from the TEG even from very low voltages. However, when the battery is at low voltages it creates another problem. To maximise the power output from the TEG the load resistance should match the TEG resistance at all times. One reason for selecting this particular battery was that the battery voltage of 3.4 V is close to the matched load voltage of the TEG, even over a wide range of TEG temperatures (O'Shaughnessy et al., 2014). In accordance with the circuit diagram shown in Fig. 6, the battery and fan are connected in parallel to the TEG. Thus the battery (the load) dictates the TEG voltage when no appliance is connected to the USB port. Furthermore, the TEG and fan voltages remain almost identical. If the user burns in the TEG-stove after the battery has been discharged to low voltages, the battery will operate at very low voltages which results in almost no cooling of the generator.

As seen in Fig. 16, the battery and peak TEG voltages are above 3 V when the stove is in use. The TEG voltage fluctuates as the temperature difference across the TEG varies. An appliance is connected at approximately 12:15 and battery voltage begins to drop. Although the TEG stove is still in use, the TEG voltage after the appliance charging is significantly lower (~2 V) than beforehand which in turn regulates the fan voltage. This causes a slower-rotating fan which has the knock-on adverse effect of the higher cold side TEG temperatures observed in Fig. 14b. Over time this leads to over-heating of the generator which manifests as fan case melting and eventual breakdown of the solder within the TEG modules. The cycling of the battery voltage below recommended limits is also deleterious with respect to battery life.

This circuit is not designed to operate with the battery at low voltages, and this behaviour was not replicated in the lab prior to deployment. In the previous field trial electricity supply exceeded demand and the situation described above was not encountered because the primary battery was typically at a high charge level. In the current study, the battery is regularly flat due to electricity being in huge demand. This extremely useful information will inform the next iteration of the charge control circuitry.

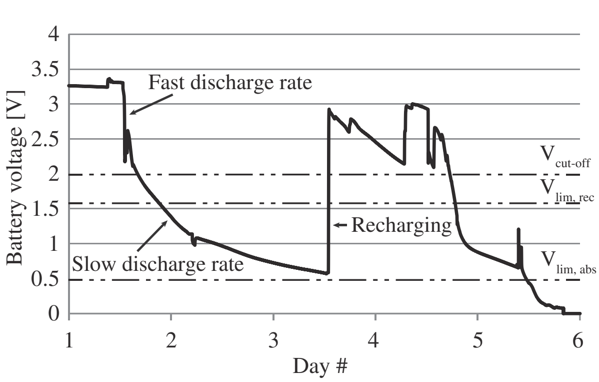

Fig. 15. Battery voltage for TEG-stove 7 over a 6-day period.

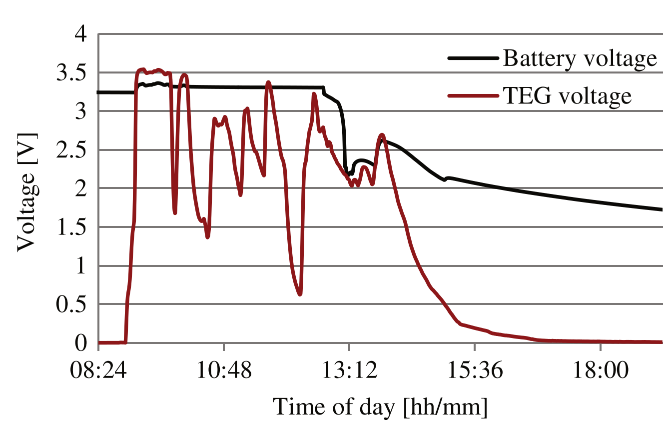

Fig. 16. Effect of battery voltage on TEG voltage.

Outlook

Even the current heat sink design protrudes noticeably from the stove wall. Reducing its profile is desirable, although a negative consequence of this approach may be an increase in radiant heat transfer from the stove wall. Furthermore, the heat sink used in this study is still expensive and not available locally in Malawi. A fan-based cooling method, although providing adequate cooling, represents moving parts which are a likely source of failure. Furthermore, disconnecting the fan from its original motor and mounting to the low power DC motor is a cumbersome and time-consuming task. The ideal cooling method for this application would be passive, inexpensive and simple to manufacture and instal.

The $LiFePo_4$ battery is also expensive and not readily available in Malawi. Other rechargeable batteries could be investigated such as lithium-ion or nickel-metal-hydride (NiMh), although a modular circuit design may be required since placing these batteries close to the stove is not recommended due to safety considerations. The inclusion of a rechargeable battery offers users the ability to 'cook now charge later', but many of the field trial participants chose to charge their devices whilst using the stove, essentially bypassing the battery. This raises questions about the capacity and indeed the need for any battery at all. Removing the battery and simply using direct charging from the TEG is another option that will be studied in the next design iteration.

For any design, it has become apparent that educating the users in correct TEG-stove and circuit operation and maintenance is critical. Undoubtedly, the simple circuit design is not capable of managing the charge control in the longer term without resorting to significant training. This was not evident during a previous field trial of the generator. During the current study, the batteries were over-discharged and frequently left in a discharged state for many days. Established maximum power point tracking techniques will now be investigated and improvements will be made in battery discharge protection (if needed) and boost efficiency. A lab experiment will also be designed to perform longer term performance analysis.

The long term research objective is to develop an electricity generator that is affordable to the target market. Solar panels, solar lanterns and medium powered hand crank generators exist which have the potential to provide lighting and phone charging capabilities for off-grid rural communities. However, issues such as high capital investment, theft and long term reliability and maintenance have hindered penetration of these technologies. Unlike solar panels, TEGs can produce power both during the day and at night regardless of the weather. Commercially available TEG-stoves and pots also exist, but they appear to be aimed at the developed world and the outdoor camping markets, such as the BioLite (>$120) (BioLite Inc., 2015) and the Wonderpot (>$100) (Okamoto, 2013). For future iterations of the generator design in this study, an in-volume price target of $25 ~ $30 is feasible, which would result in a payback period under one year considering how much disposable income is spent on phone and lighting in sub-Saharan Africa (Adkins et al., 2012).

In collaboration with Concern Universal, the next phase of the research will also involve local manufacturing of some of the heat collection and dissipation components, as well as the development of a business model and engagement of local entrepreneurs regarding the possible marketing, selling and distribution of TEG-stoves to the communities. As the number of the TEG stoves available to end users during the pilot phase increases it will be important to track and understand any shifts in social, cultural or power relations between users and their broader community because of the introduction of the TEG.

Conclusions

Ten locally-made cooking stoves were retrofitted with a thermoelectric generator and deployed to rural villagers in Malawi. The generator design was less expensive, mechanically more robust and easier to assemble than the initial design. Each generator stove was equipped with a USB port for appliance charging and data loggers which enabled measurement of the stove usage and power consumption. None of the stoves were used every day, indicating that the users operated other stoves and/or cooking methods based on their preferences. Users were able to charge their mobile phones, lights and radios. Similar to the first field trial, TEG-stove usage was again erratic but intense. Some of the users generated extra income or eased community tension by charging their neighbours' mobile phones. The users did not appear to operate the TEG-stoves solely for electricity production, but they preferred to charge their devices when the stove was in use rather than wait and use the energy stored in the battery. The users consumed up to 4.5 W·h per day, which represents a 50% increase compared to the previous field trial.

Many of the TEG-stoves experienced greater cold side TEG temperatures than expected. Several stoves failed ultimately due to a circuit problem which meant that the battery over-discharged beyond a threshold voltage. The information gathered from this study has subsequently been used as part of the adaptive design process to redesign the generator and charging circuitry for a third field trial scheduled in 2015. The re-engineered generator will include components manufactured by a local Malawian workshop which will dramatically reduce the cost of the generator. On the other hand, the 'simple' charge control circuitry is now deemed unfeasible and a new circuit has been under development which offers maximum power point tracking along with additional utilities, such as user selectable 3.5 V and 5 V and on-board time-stamped data logging.

Nomenclature

Symbol	Description	Unit
P_{USB}	Power consumed by user via USB	W
R_L	Load resistance	Ω
R_{TEG}	TEG internal resistance	Ω
T_h	Module hot side temperature	°C
T_c	Module cold side temperature	°C
$T_{chamber}$	Combustion chamber temperature	°C
$V_{cut\text{-}off}$	Recommended cut-off voltage	V
V_{lim}	Recommended voltage limit	V
$V_{lim,\ abs}$	Absolute voltage limit	V
ΔT_{TEG}	Module temperature difference	K
α	Seebeck coefficient	V/K
α_{eff}	Effective Seebeck coefficient	V/K

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