FIELD TRIAL TESTING OF AN ELECTRICITY-PRODUCING PORTABLE BIOMASS COOKING STOVE IN RURAL MALAWI

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Abstract

A novel off-grid electricity-producing device has been designed for integration with biomass-fuelled improved cooking stoves commonly in use in the developing world. The device operates on the thermoelectric principle whereby small amounts of electricity can be produced in response to a temperature difference across a thermoelectric generator, or TEG. The energy produced by the integrated generator can be used for direct charging or stored in a rechargeable lithium-iron-phosphate (LiFePO₄) battery. The generator is equipped with a standard USB output which allows the user to charge a variety of 5 Volt appliances. Five technology demonstrator electricity generating stoves have been integrated with locally produced clay cooking stoves in the Balaka district of Malawi, Africa. This study details the results from an 80-day field trial of the devices. The data reveals that the stoves are in use for a greater time than was anticipated. The data also indicates that the generators perform adequately in the field and provide the user with the ability to charge LED lights and mobile phones from the generator stoves every day if necessary.

Keywords

Biomass, Cook stove, Thermoelectric, Electricity Generation, Lighting, Phone Charging

1. Introduction

As discussed by Bhattacharyya (Bhattacharyya, 2012) there is a general consensus that access to reliable and clean energy services to the population is critical to achieving sustainable development. Even still, the World Health Organisation (WHO) estimates that over 20% of the global population (~1.5 billion people) lack access to electricity. Furthermore, 40% of the global population rely on the traditional use of biomass for cooking (OECD/IEA, 2010, WHO, 2011). Evidently there is still much work to do with regard to energy access for emerging countries, where there are literally billions of people living without access to vital energy services (Bhattacharyya, 2012).

A key building block of the United Nations Millennium development goals (MDG) is making improved cooking stoves widely available (WHO, 2006). Improved cooking stoves reduce the amount of fuel used and can have other benefits such as improved indoor air quality (IAQ). Many studies have been performed which clearly show the benefits of improved stove designs on stove fuel consumption. For instance, MacCarty et al. (MacCarty et al., 2010) showed that rocket-type stoves can reduce fuel use by 33% and forced air stoves can reduce fuel use by 40% compared with 3-stone fires. Similar findings were reported by Adkins et al. (Adkins et al., 2010b). This has implications with regard to the environmental impact of cooking since it is related to CO₂, black soot and deforestation. For example, Venkataraman et al. (Venkataraman et al., 2010) state that 4% of India's CO₂ could be avoided if clean cookstove initiatives were carried through. Further to this, there are other aspects such as costs associated with purchasing and collecting wood. Reducing fuel consumption in turn reduces the workload of those people who have to gather and carry the wood back to

the household. This has other positive side effects: in many cases it is women and young girls who must travel far and wide to collect fuel (Warwick and Doig, 2004). By reducing the amount of time spent on this task it also lessens their risk of gender based violence and their potential vulnerability to HIV & AIDS (Patrick, 2006).

In addition, research has shown that improved cookstoves can reduce emissions of toxic gasses and harmful particulates (MacCarty, Still, 2010). Although there is still some debate regarding the relation between clean cookstoves, IAQ and health, Adkins et al. (Adkins, Tyler, 2010b) estimate that about 570,000 premature deaths of poor women and children in India could be avoided if clean cookstove initiatives were in place today. Singh et al. (Singh et al., 2012) also report changes in cough, phlegm, and eye irritation in improved cookstove users in Nepal.

In 2009, 69% of people in sub-Saharan Africa (SSA) lacked access to electricity, ranking it lowest of its population compared with emerging countries from other regions (Onyeji et al., 2012). In fact, most SSA countries were still using less than 20W/Capita in 2005 (Mechtenberg et al., 2012) compared with developed countries, such as the USA who used around 2000W/Capita. In the context of development, Mechtenberg et al. shows that there is a direct correlation between a country's electrical base power per capita and the country's Human Development Index (HDI). This situation is particularly prevalent in Malawi, where according to the WHO energy access report of 2009 (Gwénaëlle Legros, 2009), approximately 91% of the population have no access to electricity. Furthermore, less than 1% of the people have access to modern fuels. Families that survive with only basic lighting (e.g. candles, simple lamps and fires) lose

opportunities for educational and income-generating activities outside of daylight hours (WHO, 2006, 2012). Further to this, the penetration of mobile telephony in SSA has been increasing steadily over the past several years. Mobile phones will surely play a vital role in the development of emerging countries and these too will require access to electricity.

Electricity generating devices, such as solar panels, solar lanterns and medium powered hand crank generators exist which have the potential to provide lighting and phone charging capabilities for off the grid rural communities. However, in Malawi, issues such as high capital investment, theft and long term reliability and maintenance have hindered penetration of these technologies meaning that most homes without grid connectivity lack household electricity (Adkins et al. , 2010a). A viable technology should be available at an appropriate cost, have the ability to be secured in the home or difficult to steal and be manufactured and maintained close to the end users. With regard to this last point, a technology that is straight forward enough to be manufactured and distributed by small local business ventures in rural communities would bring commerce to the region, allow for large scale distribution in the difficult-to-access rural areas and allow for maintenance and repair which supports sustainability of the technology.

This study details the deployment and field testing of a novel thermoelectric generator technology demonstrator that has been integrated with an improved cooking stove commonly used in Malawi. The generator is technically straight forward, has the potential to be low cost in large volumes (<\$25 US), is easily assembled and repaired and provides sufficient electrical energy for daily phone, LED lantern and low powered radio charging. The main objectives of this study are to:

- Deploy the technology demonstrator stove generator system to participant families in Malawi for a period of up to 3 months.
- Simultaneously deploy non-generator stoves fitted with data logging equipment.
- Log all stoves' usage and power generating performance over time.
- Evaluate stove use and TEG-stove performance.

2. Review of TEGs and stoves integration

In the literature there exists some work related to electricity generation from biomass cooking stoves in the developing world. Mastbergen (Mastbergen, 2008, Mastbergen et al. , 2005) developed and field tested a TEG-stove generator system with the objective of generating 45 Whrs of electrical energy using two 14.7 Watt TEGs and a fan cooled aluminium heat sink. The field trial results showed variable degrees of success and failure of the system, with the later associated with thermal cycling and battery failure due to incomplete charging. The technology was subsequently redesigned with an estimated cost of 170 USD in high volumes. Lertsatitthanakorn (Lertsatitthanakorn, 2007) investigated a TEG-stove system under laboratory

conditions and was able to generate a just under 2.5 Watts, though no charge control circuitry and associated battery charging capacity was developed or tested. Although no field trial tests were performed, Lertsatitthanakorn estimated a payback period, compared with the equivalent of battery use, of less than one year.

Champier et al. (Champier et al. , 2011, Champier et al. , 2010) developed a TEG generator for eventual use in biomass cook stoves in developing countries. Using heated gas to replicate the exhaust gas of a biomass cook stove their system was able to produce up to 7 Watts of electrical power from a single TEG rated at 10.5 Watts. In (Champier et al. , 2013) the authors investigated maximum power point tracking, and tested the MPPT DC/DC converter on the prototype TEGBioS technology in a laboratory setting. To our knowledge, no field trials have been performed.

Chen et al. (Chen et al. , 2013) have developed a potential low cost cook stove technology with the capacity of generating in the region of 23 Watts of electricity using a thermo-acoustic engine. The work describes a completely integrated stove-generator system suitable for manufacture with a projected cost of between 160 USD to 240 USD. They do discuss design changes for the stove and generator system which have the potential to reduce this cost to the region of 100 USD, though these have yet to be implemented.

2. Stoves selection

An article appearing in The Economist Technology Quarterly stated that "If user demand were the sole driver of innovation, the biomass cooking stove would be one of the most sophisticated devices in the world."

Cooking fires are an integral element of any rural household as they provide heat, light, and cooking facilities. Currently, there is a global initiative to improve the fuel efficiency and emissions characteristics of traditional three-stone cooking fires (Figure 1(a)) by replacing them with efficient and portable cook stoves. However, these cooking stoves can also have harmful social and environmental consequences if they are not culturally or environmentally sensitive.

Shown in Figure 1(b), the chitetezo mbaula is a clay cooking stove that is produced locally in Malawi. This particular stove is promoted by Concern Universal and other development organisations as being a safer and superior alternative to the traditional three-stone fire cooking technique.

Figure 1 location

Since 2008, Concern Universal has worked with mostly rural communities to produce and market close to 20,000 chitetezo stoves. The stoves are available in five districts nationwide in Malawi with the majority produced, distributed and sold in the Balaka district as part of the Msamala Sustainable Energy Programme (MSEP). Typically, women's groups produce the stoves as an income generating activity which can supplement their largely agricultural based income. The stoves are then sold locally to middlemen who distribute them over a wider geographic coverage at a small profit.

Projects in the Dedza and Ntcheu districts are funded by Irish Aid while MSEP is funded by the EU and Foundation Ensemble. These are integrated rural development projects with the objective of linking health, agriculture and environmental sustainability initiatives to increase household food security and build households' resilience to climate change by reducing the negative environmental impacts of the use of biomass fuel normally sourced from local woodlots and forests.

The chitetezo mbula provides a range of benefits to the rural households when compared with the traditional three-stone fire. Furthermore, its acceptance within rural communities makes it a prime candidate for investigating the performance of a stove-based electricity producing device. For these reasons this particular stove was selected as the heat energy source for the thermoelectric generator technology.

In June 2013, Malawian President Joyce Banda signed up to the Global Alliance on Clean Cookstoves (United Nations Foundations, 2013) initiative to encourage 100 million households 'to adopt clean and efficient stoves and fuels by 2020' and committed to have 2 million improved cookstoves in Malawian households by 2020. One barrier to achieving this goal is peoples' reluctance to replace the traditional three stones fire with new technologies due to social and cultural perceptions (Concern Universal, 2011). However, many development organizations such as Concern Universal feel that the added value of being able to generate electricity and potentially gain economic benefits from a chietezo mbuala stove will provide the social and economic incentives to rural households to adopt improved cookstove technology.

3. Thermoelectricity overview, thermoelectric module and battery selection

The design of the TEG-stove technology demonstrator is discussed in detail in a recent article by the current authors (O'Shaughnessy et al. , 2013) and only the relevant features will be discussed herein so as to keep the focus of the current work on the field trial results. In short, the TEG-stove technology was designed to be capable of producing up to 5.9 Watts of electrical power and store roughly 9 Whrs of electrical energy over three one hour cooking periods. This amount of electrical energy is enough to keep a mobile phone and a LED lantern charged every day. The method by which this is achieved is summarized below.

Thermoelectric generators (TEGs), such as that shown in Figure 2, are solid-state energy devices that contain no moving parts. They convert heat directly into electricity by a process known as the thermoelectric effect.

Figure 2 location

To generate electricity, a temperature difference must exist between the two faces of the TEG, traditionally named the 'hot' and 'cold' surfaces. The working principle is depicted in Figure 3. TEGs consist of arrays of positive (p-type) and negative (n-type) semiconductor thermocouples. In the figure, a single thermocouple is clamped between a heat source and a heat sink. Heat flows from the heat source through the module and is dissipated by the heat sink, and electricity is produced by the device. Greater temperature differences produce greater amounts of electricity. Increasing the number of thermocouples also increases output. Hence TEGs are available in a range of shapes, sizes and output power ratings; however their power conversion efficiency is low, typically in the range 2-5%. This means an output of approximately 2~5 Watts of electrical power for every 100 Watts of heat flow through the device.

Figure 3 location

For this study, the chosen TEG is supplied by Thermal Electronics Corp, Canada. In low numbers, the unit cost of this generator is approximately 49 USD which reduces to 8 USD in high volume (~10,000 units). Some specifications for the module are provided in Table 1.

Table 1: TEG 12610-5.1 supplier specifications

Dimensions	40 mm x 40 mm
Open circuit voltage	8.6 Volts
Internal resistance	3 ohm
Match load output voltage	4.2 Volts
Match load output current	1.4 Amps
Match load output power	5.9 Watts
Heat flow through the module	~ 140 Watts
Heat flux	~8.8 Watts/cm ²
Max. continuous hot side temp.	270 °C
Max. intermittent hot side temp.	330 °C

Figure 4 plots the power produced by the chosen TEG module in response to increasing temperature difference across it. The figure details the behaviour during two separate tests. The solid black line represents the matched load power. This means that the resistance of the load matches the internal resistance of the TEG at all times and therefore the power obtained is the maximum power the module can produce at each temperature difference (Kinsella et al. , 2014, O'Shaughnessy, Deasy, 2013).

Figure 4 location

The 'stove generator' data is the actual power generated by the TEG and associated circuitry during normal

operation in the generator stove. In this case there is no matched load, and maximum power is not obtained at each temperature difference. However, the circuit and battery was designed to have a resistance approximating the matched load resistance at higher temperature differences. This means that at large temperatures differences across the TEG, the generator can still produce close to maximum power. Further detailed description, mathematical modelling, performance testing and analysis for this TEG can also be found in (Kinsella, O'Shaughnessy, 2014, O'Shaughnessy, Deasy, 2013)

The TEG is intended to be used as a power source to charge a rechargeable 3.3 Volt lithium-iron-phosphate (LiFePo₄) battery, specifically the ANR26650 cylindrical cell manufactured by A123 Systems, termed the 'primary' battery henceforth. LiFePo₄ batteries are known for their good safety characteristics and long life cycles. They can also be left in a partially discharged state for extended periods without causing permanent damage. Some battery specifications are provided in Table 2.

Table 2: LiFePo₄ battery specifications

Cell dimensions (mm)	ϕ 26 x 65
Cell mass (g)	72
Cell capacity, nominal/min. (Ah)	2.3/2.2
Voltage, nominal (V)	3.3
Internal impedance (mΩ)	8
Max. continuous discharge (A)	70
Operating temperature (°C)	-30 ~ 55
Typical cycle life	>1,000 cycles

4. Overview of heat collection and dissipation strategy

A sketch of the generator assembly is provided in Figure 5(a) and the integrated TEG-stove concept is illustrated in Figure 5(b). Henceforth the term 'generator' refers to the whole device, including the heat collection and dissipation components and the TEG.

Figure 5 location

The generator assembly comprises a 12610-5.1 TEG clamped between two 50mm x 50mm x 3mm copper plates. Heat is collected from the fire and delivered to the hot side of the TEG through three copper rods which protrude into the centre of the stove. The rods collect heat from the fire by conduction and radiation, and are raised above the base of the stove as depicted in Figure 5(b). It is intended that the rods act as a grate which should lead to a cleaner burn as this configuration allows more air to be drawn up through the fuel. The quality of the burn is also influenced by the use of a stick rest such as a brick. Users in the field trial were encouraged to use a stick rest in conjunction with the copper rod grate.

A thin sheet-metal skirt is placed on the inside of the stove as shown in Figure 5(b). The sheet serves a dual purpose by preventing heat from escaping to the walls of the stove and also by reflecting this heat back to the centre of the combustion chamber.

To maintain a temperature difference across the TEG, the copper plate on the cold side is thermally connected to a commercially available Arctic Cooling Freezer 13 CPU heat sink. The 92mm fan impeller was modified with a low power DC motor which is capable of driving the fan from voltages as low as 0.3 Volts. This not only reduces the amount of power required from the TEG to drive the fan (~ max. 0.5 Watts), but also initiates the cooling almost immediately once the fire is lit. This would not be possible if conventional fan motors were used, which require a starting voltage of over 3 Volts and would thus require ancillary electronics to begin rotating until the required voltage is generated by the TEG itself. A finger guard (not shown) is placed in front of the fan to prevent injury.

The generator is mounted toward the back of the chitetezo mbaula so that the handles can remain intact. The thickness of the walls is such that removing a small section does not markedly weaken the stove.

5. Primary battery charging circuitry

The battery charging circuitry utilised in the technology demonstrator generator stove was designed to be as uncomplicated as possible whilst providing the basic charge control and safety functions (Kinsella, O'Shaughnessy, 2014). A circuit diagram is provided in Figure 6. In this scenario, the TEG may be viewed as a DC power source.

Figure 6 location

The circuit includes the following features:

- 0.005 ohm sense resistors enable 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.
- A Schottky diode prevents the battery from discharging to the TEG.
- A Zener diode prevents battery overcharge by bypassing the battery when the battery nears full charge.
- A thermal switch open-circuits the battery if the battery temperature exceeds 60 °C.
- Two pairs of indicator LEDs are installed on the front panel of the circuit box, facing the user as they operate the stove (see Figure 7). Red LEDs indicate when the TEG voltage is sufficient to charge the battery. Green LEDs indicate full charge.
- DC-DC converter which boosts the output voltage to a more useful 5 Volts, and is connected to a single male USB port.

Due to power drains from the fan and diodes and charging inefficiencies, it is estimated that ~60% of the power generated by the TEG can be stored in the battery when no load is connected to the USB port, though this will depend on the charge level of the battery. On average, the fan requires approximately 12% of the power generated by the TEG. The 3.9 Volt Zener diode can consume over 20% of power which is undesirable. Unfortunately this particular Zener leaks current from voltages as low as 3 Volts. As the battery approaches full charge, the Zener diode allows more and more current to bypass the battery to prevent overcharging. Further information can be found in (O'Shaughnessy, Deasy, 2013).

Figure 7 location

5.1 Data acquisition

In order to gain real-life performance data during the field trial each generator stove is equipped with four data loggers. A four-channel thermocouple logger records the hot and cold side TEG temperature, the stove wall temperature and the temperature inside the combustion chamber. These temperatures enable calculation of the approximate temperature difference across the TEG, and also provide critical stove usage information.

The generator stoves are also equipped with three voltage loggers which measure the TEG voltage and current and the current delivered from the USB port. This enables calculation and tracking of both the power generated by the TEG and the power consumed by the user. The loggers are housed in a flame-retardant aluminium box which is mounted to the outside wall at the back of the chitetezo stove. A thin sheet of metal is placed between the logger boxes and stove wall to prevent overheating of the data loggers due to heat transfer from the stove walls. All data loggers were set to record at a rate of 1 reading per minute for the duration of the 80-day field trial.

5.2 Appliance charging

Access to light and communication technology are of vital importance to the developing world (WHO, 2006). This study focuses on the ability to charge rechargeable LED lights, mobile phones and even radios from a cooking stove using a familiar USB 5 Volt port. In (O'Shaughnessy, Deasy, 2013) it was shown that a fully charged generator stove battery is capable of completely charging from flat a Sun King LED lantern. The LED lantern contains a 3.7 Volt, 0.75 Amp hour (~2.8 Watt hour) battery, and charging from the generator stove typically takes 2 hours with sufficient energy remaining for an additional 40 minutes of mobile phone charging. For the Malawi field trials the participant families were supplied with Sun King LED lanterns and a USB cable with several different mobile phone connectors. A mobile phone commonly encountered in Malawi at the time of the field trial is the ZTE, containing a 3.7 Volt, 0.4 Amp hour (~3.3 Watt hour) battery.

Details of the Ireland-based laboratory experiments with the generator stoves can be found in (O'Shaughnessy, Deasy, 2013) where it was shown that the TEG produced a maximum of 5.9 Watts of electrical power. On average, approximately 3 Watt-hours of energy was stored in a battery during each 1 hour long experiment. It was anticipated that approximately three hours of stove usage could be enough to fully charge the primary battery, although it is noted that this value is dependent on uncontrollable factors such as user operation, ambient temperature etc.

6. Malawi field trial: background information

The field trial was conducted in the Balaka District with the support of Concern Universal Malawi, who carefully selected the participants. The participants in the study were purposively selected using a simple socio-economic criteria framework that included their willingness to participate in the study, their acceptance of the new technology, having a telephone that they normally incurred costs to charge, and having school going children who would benefit from a light to study in the evenings. If people did not fit these basic criteria they were excluded from the study. Five generator stoves were deployed to five families in the village of Mponda on Monday 12th December 2011. This group is termed the 'treatment group'. Two days later, five non-generating stoves equipped with temperature data-loggers were deployed in the village of Dulani to form

the 'control group'. The treatment group participants were asked to replace any existing stoves with the new generator stoves until the end of the trial.

A short questionnaire was completed with the treatment and control groups prior to deployment of the new stoves. This provided background information on typical stove, light and mobile phone usage for each participant. There was a consensus throughout both groups that cooking stoves were used three times per day on average. The estimated usage time varied widely however. Most families possessed at least one mobile phone, whilst a range of lighting methods were encountered such as candles, paraffin lamps and battery-powered LEDs. Many participants had to walk long distances and then pay money (typically 50 MWK ~ 0.13 USD) to a local person to charge their mobile phone.

6.1 Malawi field trial: reliability

It should be noted that the generator of stove 2 suffered a mechanical failure after just over a month and was replaced with a backup TEG-stove, though the back-up did not have data logging equipment. The cause of the failure was due to the heat sink. This commercially available CPU heat sink contains a base plate used for mounting to motherboards. The base plate is soldered to the heat pipes. On stove 2, it was noticed that on the cold side of the TEG, the soldered connection between the heat pipes and the base plate had failed. This meant the heat removal from the cold side of the TEG decreased dramatically until the TEG burned out. At the time of the authors' last visit to Balaka, Malawi, which was six months after the field trial deployment, all five TEG-stoves were still in operation and still being used as they were designed.

6.2 Malawi field trial: stove usage

The data from both the treatment and control groups was collected on Wednesday 29th February 2012. As mentioned previously, the data loggers captured temperature and power information every minute since deployment. Figure 8 plots the data collected for TEG-stove 4 on a randomly selected day, in this case Sunday 29th January 2012. From the temperature graph it can be seen that the stove was used in several stages and the total use for this particular day is well in excess of three hours, which was the design point of the generator. It must be clarified at this point that the term 'usage' means that the stove was burning fuel – it is not known if the user of the stove was attending to it at that time. The duration of the cooking periods would be expected to vary with the type of meal cooked and the number of diners, and probably also with the time of year. Indeed on this particular day it appears that the stove was 'hot' from 6am until almost 9am with three other usage periods ending at about 8pm.

Figure 8 location

Temperature profiles such as that shown in Figure 8 enable calculation of the number of usage periods and usage time. These numbers are obtained by analysing the individual daily temperature profiles for each stove and identifying distinct periods where the stove temperature is much higher than ambient. For example, Figure 8 shows that TEG-stove 4 was used on four distinct occasions on 29/01/12.

Another stove usage profile is given in Figure 9 for comparison. Here the stove is 'hot' from around 6am to 3pm, with an additional use at around 7pm. This type of temperature profile has been frequently observed across both the treatment and control groups, and may result from the stove being tended to irregularly or used for means other than cooking (such as heating water, space heating, light, insect repellent) in between the main meal times.

Figure 9 location

Table 3 and Table 4 display the number of distinct stove usage periods for both the treatment and control groups over the duration of the trial. The total represents the sum of all the individually identifiable stove usage profiles over the entire trial. The average refers to the average stove usage periods per day over the course of the field trial. It must be noted that the average takes into account only those days where the stove is in use. The maximum signifies the largest number of distinct stove usages on any given day.

Table 3: Number of distinct stove usage periods (treatment group)

Stove	1	2	3	4	5
Total	225	67	67	237	100
Avg.	3.0	1.5	1.5	3.0	1.8
Max.	6	3	4	5	4

Table 4: Number of distinct stove usage periods (control group)

Stove	6	7	8	9	10
Total	213	103	222	66	52
Avg.	3.0	2.0	3.0	1.0	1.0
Max.	5	4	6	3	4

Evidently, there is much variation in stove usage across the families in both groups. Indeed, only two families from each group seem to have used the provided stove as their only cooking stove. Interestingly, the average number of distinct usage periods for the frequently used stoves is three times per day, which was the baseline answer given by most families in the pre-deployment questionnaire.

Power generation predictions in the laboratory setting were based on three one hour-long usage periods per day. Figure 10 clearly shows that the actual usage per day is much greater. On any given day during the field trial, all stoves, even the infrequently used, are in operation for more than 3 hours per day. In some cases the stoves were in use for up to 18 hours on a particular day. This has significance not only in terms of the possibility of generating power, but also indoor air pollution, fuel gathering time and fuel consumption. Moreover, since the behaviour is similar across both groups, the lengthy stove usage may not be solely attributable to the inclusion of a power generating device. Indeed, prolonged stove usage was encountered more frequently in the control group.

(a) Treatment group

(b) Control group

Figure 10 location

6.3 Malawi field trial: TEG generator performance

The power produced by the TEG module is linked to the temperature difference across it. The largest power output from the TEG corresponds to the point at which the temperature difference between the hot and cold side

of the TEG is greatest. Therefore, the ambient temperature is important since ambient air is drawn by the fan to cool the generator and defines the coldest point in the thermal network. The TEG performance will also depend on the combustion chamber temperature because it is related to the highest temperature in the thermal network. Thus, the TEG generator performance will be less if either/or the ambient temperature is higher or the combustion chamber temperature is lower. With this in mind, compared with experiments conducted in Ireland where the generator technology was developed, the peak power and total energy generated in a given time frame in the field is lower (O'Shaughnessy, Deasy, 2013). However, this was expected since the ambient temperature in Balaka in December was regularly in excess of 30 °C, which limits the cooling capacity of the fan and heat sink. Furthermore, the combustion temperatures in Ireland were of the same peak magnitude (~800 °C) though the fire was carefully tended to during the experiments and ash and charcoal was not allowed to build up within the combustion chamber. In the field trials the chamber temperatures, and thus TEG hot side temperatures, fluctuated considerably. This is possibly due to the fact that the stove user was responsible for various other duties (meal preparation, minding children etc.) during the cooking periods. Importantly however, the stoves tested in Malawi performed to a comparable level, and the charging circuitry worked as intended, though further improvements are necessary.

Figure 11(a) shows the temperature histories measured in TEG-stove 1 on 20/12/2011. As discussed, on this day the stove was 'hot' for significantly longer than 3 hours. It is noted that there is relation between the chamber temperature and the TEG hot side temperature. The maximum TEG hot side temperature reached ~240 °C when the stove chamber temperature reached around 700 °C. Generally however, the TEG hot side temperature remained between 100 °C and 200 °C, which is below the ideal temperature range for maximum power generation from this TEG. The cold side TEG temperature also depends on the chamber temperature but not as strongly as the hot side. It remained 20-30 °C above ambient which at times exceeded 40 °C on this day.

(a) TEG-stove temperatures

(b) Power produced/consumed

(c) Power produced/consumed

Figure 11 location

Figure 11(b) plots the associated power profiles for this stove on this representative day. The power generated by the TEG and the power consumed through the USB port are plotted. The TEG voltage is also plotted on the secondary vertical axis. Of particular concern is the quality of power generated. Typically, the battery requires a supply voltage above 3 Volts to charge, and the DC-DC converter from the battery to the USB charging port also requires a similar input to step up to 5 Volts for charging electrical appliances. From the voltage plot it is clear that despite the TEG hot side temperatures not reaching the ideal operating point, the TEG voltage is above 3 Volts for extended periods and fluctuates roughly in phase with the stove chamber temperature. This is of course expected since the voltage is related to the temperature differential across the TEG which is related to the chamber temperature. Even still, the TEG voltage is also a function of the electrical resistance in the circuit and therefore a function of the battery charge level, but the dominant factor is the temperature difference across the module. The same thing can be said about the TEG power plots since the power is related to the voltage.

On this day, a maximum ~ 4.5 Watts of power was generated. The instantaneous TEG power was very sensitive to the chamber temperature, which is of course coupled with the person using the stove and caring for the fire. Interestingly, the power spikes are largest at around 6am, 12pm and 8pm which likely correspond with the three main meals; times when the stove user tended to the fire. Figure 11b also reveals that the user of TEG-stove 1 charged an appliance on two separate occasions on this particular day, once for approximately two hours and once for approximately 40 minutes. The charging profiles indicate that the first device charged was the Sun King LED lantern, which typically charges for 2 hours at a constant 2~2.5 Watts if charged from flat (O'Shaughnessy, Deasy, 2013). The second device charged is likely a low power demand mobile phone, which initially consumes 2.5 Watts of power.

It is noted that the first charge was performed when the stove was not being used, in that the participant used the energy that was stored in the battery. The second charge was performed when the stove was still in operation where the TEG would then be direct charging the phone as well as charging the battery. The fluctuation in the power consumption curve at the end is due to the DC-DC converter attempting to charge in many small bursts. This behaviour is down to either/both of the following factors:

- Insufficient power generated or stored in the battery
- Mobile phone is fully charged

In order to give a sense of the supply and demand associated with this stove on this day, Figure 11(c) plots the integrals for power produced by the TEG generator and consumed during charging of an appliance for this day. Immediately one can see the distinction. The TEG produced over 11 Whrs; of which between 50% - 60% would be routed to the battery if no appliance is being charged. Evidently this participant only used 5 Whrs charging appliances. This is an interesting result, since it points to the possibility that in some instances the TEG-stove generator system is capable of supplying more electricity than is required by the family at the time of testing.

7. Energy supply and demand

The energy produced and consumed for each of the treatment group stoves is displayed in Figure 12 for the entire duration of the field study. The figure shows very clearly that there is a wide variation in the energy generated, which is directly related to the stove usage. Interestingly, the energy-time plots are all quite linear which shows that the rate of energy production is more or less constant and is evidence that stove use behaviour is consistent over time. It should be noted that the logging of generator stove 2 ended after just over a month for reasons explained previously and this is why the power-time curve flat-lines.

Figure 12 location

Clearly, stoves 1 and 4 produced the most electrical energy. Each stove was used about 230 times over the trial period and used on average eight hours per day (see Table 3). Figure 12(a) shows that each generator produced energy at nearly the same rate and totalled ~ 700 Whrs after 80 days. It is likely that the participants using stoves 1 and 4 continuously used the TEG-stove as the primary cooking stove for the entire trial whereas stoves 3 and 5 appear to have been used intermittently since they produced energy at a notably lower rate, culminating in about 250 Whrs each over the trial period. This is highlighted in Figure 13 where, for stove 3, the TEG power produced and USB power drawn from the battery are plotted together for the duration of the study. Upon revisiting the participant to collect the data, the user of stove 3 said that she valued the stove greatly and only used it when she needed to produce electricity. As evident in Figure 13, power is consumed through the USB only when it is being generated by the TEG. This being the case, the stove 3 user would be expected to have a fairly well balanced energy supply and demand profile, which is in fact the case. Figure 12(c) and Figure 13 show this clearly as the total energy produced is only about 25% larger than that consumed. Since this user directly charged her appliance while burning in the stove

rather than using the energy stored in the battery, this 25% is roughly the amount required to run the fan and peripheral electronics within the generator system, accounting for losses. It can thus be said that the stove 3 participant used virtually all of the energy that she produced. This averages to 2.5 Whrs per day. Interestingly, this level of electricity demand is fairly consistent across the treatment group, where it ranges from 1.5 Whrs/day (stove 5) to 3.3 Whrs/day (stove 1).

Figure 13 location

As mentioned in (O'Shaughnessy, Deasy, 2013), the design point for the TEG-stove technology was to supply 9 Whrs/day to service a Sun King LED lantern and a mobile phone. Each participant household was supplied with the LED lantern and each had at least one mobile phone. Evidently, the design point of 9 Whrs is about 3 times more than is actually being used by this sample group. What is interesting is that, compared with the controlled experiments performed in Ireland where the system was designed, the TEG-stoves performed worse in the field. The reasons for this were discussed above. Even still, the poorer performance can be more than offset by the fact that in the field the stoves were used longer than three hours and, in the cases of stove 1 and 4 which were likely used continuously, produced an overabundance of electrical energy. The implications of this are:

- The TEG-stove is somewhat future proof with respect to additional low powered devices being acquired by these rural families.
- The excess electrical energy could be used to charge other people's phones and become an income generating activity for the household.
- The cooling system of the current TEG-stove design could be simplified, which would adversely affect the generator performance, though could reduce the overall cost of the technology.

8. Future outlook

Post-deployment surveys of the TEG-Stove treatment group indicated that the technology was valued by the users and provided adequate electrical service for daily use. Technically, the majority of the TEG generators produced electricity for the duration of the field trial which is an early indicator that it has the potential to be sustainable for long term use. Even still there are issues which need to be addressed in order to make this a viable technology for large scale deployment. These are listed below:

8.1 Cost

The majority of the cost of the current system is associated with the TEG and the cooling system. The TEG, which would cost ~8 USD in high volume is unavoidable though may reduce as the technology and associated manufacturing processes improve. The current cooling system cost must be reduced. However, based on the energy use data collected it is possible to engineer a lower performance and lower cost cooling system. This of course would reduce the overall electrical energy output, which appears to be in excess in the current design, though could be counterbalanced by a significantly reduced overall cost.

The economic viability of the technology is difficult to assess precisely. However it can be approximated conservatively by simply considering phone charging. In rural Malawi it costs approximately 50 Kwacha (0.13 USD) and survey information shows that phones are generally charged twice a week. Thus, for phone charging alone this translates to 5200 Kwacha per year (~13.50 USD). Thus, without accounting for other aspects including income saved for lighting (fuel, batteries, candles), more time for income generating activities with evening illumination and not having to travel long distances for phone charging and fuel/candle/battery collection as well as the possibility of generating income by charging neighbours' phones, the conservative payback period is around two years for a 25 USD device. Within the context of other electricity generating cook stoves discussed earlier which are approximated to cost in the region of 60,000 Kwacha (~150 USD) this is a significantly shorter payback period. Even still, more work is needed to fully understand the short term and long term cost implications of this technology which is the focus of future development of this work in progress.

8.2 Improved combustion using air cooling

In the current design the air cooling system is used only to assist the heat transfer on the cold side of the TEG and improve the electrical energy production. However, as discussed by MacCarty et al. (MacCarty, Still, 2010) introducing forced air into the combustion chamber of a biomass stove can notably improve its performance. A more holistic design may include simple modification of the cooling system and the stove such that the airflow is directed into the stove to improve its efficiency and emissions characteristics.

8.3 Reliability improvements

The soldered joint connecting the heat pipes to the base plate of the heat sink failed. It was noted also that the profile of the stove generator meant that the heat sink protruding from the stove was relatively close to the ground, which may increase the risk of it being knocked when the stove is moved.

The TEG is clamped between the heat collector and heat sink using four M5 bolts torqued to 1N/m each. Special spring washers were used to allow for thermal expansion. However, it appears that with thermal

cycling the pressure applied at the edges of the TEG was greater than the clamping pressure on the centre. This should be remedied in future designs.

8.4 Circuit improvements

The user behaviour, as typified in Figure 13, indicated that there are many instances where an appliance is connected to the USB port whilst the stove is in use and the primary battery is being charged. This behaviour and the varying nature of the fire means the primary battery will be continuously charging and unchanging at varying rates. This may be deleterious with regard to battery life and would thus have associated with it long term running costs if the battery needs to be replaced frequently. The current charge control circuitry could be redesigned to facilitate both direct charging of an appliance and battery charging when the TEG is producing electricity.

Circuit protection of the primary battery could be improved. The use of a Zener diode is a simple approach to prevent overcharging of the primary battery but there is a large inefficiency associated with it. The DC-DC converter operating in short bursts as in Figure 11 may also not be ideal and the use of a current limiter can prevent large discharge currents from the battery and protect user devices.

8.5 Life cycle analysis

Accelerated stress tests on the TEG system must be performed in order to pinpoint any mechanical or electrical failure modes which may occur and thus inform redesign of the system so that an adequately long lifetime is assured.

9. Conclusions

A thermoelectric generator technology has been developed which is capable of producing small amounts of electrical power from a biomass-fed portable cookstove. The generator has been integrated into an existing cookstove used in Malawi. Under laboratory conditions, it has been shown that for three one hour long cooking periods in a single day, the generator is capable of producing up to 9 Whrs.

Five stoves were equipped with the generator and data logging capability and deployed into a rural village in the Balaka District, Malawi for 80 days. Another five data-logged stoves (without generators) were also deployed. Stove 2 failed during the early stages of the field trial due to a mechanical failure in the cold side heat sink, and was replaced. All five stoves were operating correctly up to six months after deployment.

The data retrieved reveals that there is much variation in stove usage across the families in both the treatment and control groups, ranging from one to six usage periods per day. The average number of distinct usage periods for the frequently used stoves is three times per day. Furthermore, the length of time the stoves are burning fuel also varies across both groups, ranging from 4 to 8 hours per day on average, with maxima of 14 to 18 hours encountered on some days.

On average, the field trial generators produced less electricity compared with experiments performed in the lab. This is due to the higher ambient temperature which reduces the effectiveness of the cooling fan thus reducing the temperature difference across the module. In addition, the user behaviour meant that the stoves were tended to irregularly and charcoal was allowed to build up which reduces the TEG hot side temperature. The lower power output was somewhat offset by the longer usage periods. The five generators produced average daily powers ranging from 2.5 to over 8 Whrs per day.

Power losses due to the fan and other circuit components mean the full power produced by the TEG is never available to the user. However, the data collected over the 80 day field trial indicates that the generators performed adequately and provided the user with the ability to charge LED lights and mobile phones from the generator stoves every day if necessary. Based on the electricity use data, there is evidence to suggest that as little as 3 Whrs daily is enough energy to service the current electrical appliances for these participant families. The stoves that were used almost every day produced on average much more energy than this. This result, combined with the fact that the treatment group participants highly valued the technology and were satisfied with the electrical service provided is an early indicator that the technology has the capacity to support the energy access issue.

Nomenclature

Symbol	Description	Unit
T_h	TEG hot side temperature	K
T_c	TEG cold side temperature	K
ΔT	TEG temp. difference	K
V_{TEG}	TEG voltage	V
P_{TEG}	TEG power	W
W_{TEG}	TEG power integral	Whrs

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