Performance analysis of a prototype small scale electricity-producing biomass cooking stove

S. M. O'Shaughnessy[1], M.J. Deasy[1], V. Doyle[2], A.J. Robinson*[1]

[1]Department of Mechanical & Manufacturing Engineering, Parsons Building, Trinity College Dublin, Ireland.
[2]Concern Universal, Plot No. LK 367, Michuru Road, Blantyre, Malawi.
*Email: arobins@tcd.ie
*Tel: +353 1 896 3919

Abstract

An electrical generator has been integrated with a locally produced, biomass-fed clay cooking stove in rural Malawi. The generator produces small amounts of electricity based on the thermoelectric effect. Five demonstrator stoves were deployed into a rural community in the Balaka district for up to 6 months. This study investigates the power generation performance of the devices over the first 80 days of the field trial. It was determined that the users were able to charge mobile phones, lights and radios from the generator stoves. The power generating performance of the stoves deteriorated slightly over the 80 day period. The was due to the effects of thermal cycling on the generator system as a whole which caused eventual drying out of the thermal paste and a loosening of the clamping nuts which reduces clamping pressure and power output. One stove failed due to a mechanical problem. It was found that the power produced significantly exceeded the power consumed in most cases, which indicates an over-supply. It appears that 3 W·h is sufficient to meet the average daily electrical power requirements for the participants in this study. The data obtained from the field trial has been used to inform a redesign of the device for a second field trial.

Keywords

Biomass; cooking stove; thermoelectric; electricity generation; phone charging; Malawi

1. Introduction

In their 2010 Energy Poverty report the OECD/IEA estimated that investment of $36 billion per annum was necessary to ensure that every citizen in the world benefits from access to electricity and clean cooking facilities by 2030 [1]. The report also stated that new dedicated policies were required if the conditions for the lives of billions of people are to improve. However, to make key decisions regarding the welfare of their citizens and help refine policies over time, policy-makers rely on quantitative information and analysis [1].

Globally, approximately 1.4 billion people lack access to electricity with the vast majority living in rural areas. Furthermore, the number of people depending on the traditional use of biomass is projected to reach 2.8 billion by 2030 [1]. The problem is particularly evident in sub-Saharan Africa where the electrification level is only 31% and 80% of people burn biomass as their primary source of household energy [1].

Thermoelectric generators have recently been investigated as a method of electricity generation from biomass burning. The use of thermoelectric generators for waste heat to electricity conversion is not new, but perhaps is only now becoming more evident in everyday applications. For example, Codecasa et al. [2, 3] recently developed a 5 W, 12 V TEG system with the goal of powering an autonomous gas heater for commercial outdoor use. To date, TEGs have been predominantly limited to low power demand systems, but larger scale studies have also been carried out, such as those by Doloszeski and Schmidt [4] who investigated the use of a large thermoelectric module in combination with a fluidised bed combustor to obtain up to 450 W of electrical power.

Much of the research investigating the potential for TEGs in low temperature waste heat harvesting has been laboratory based, such as studies by [5-7]. Although the concept of integrating thermoelectric generators with cooking stoves has been investigated, many studies have focussed on optimising the TEG output under fixed parameters [8]. Although this method does offer valuable information on the performance of the generator, the test conditions are typically strictly controlled and the heat source in many cases is derived from an electrical power supply rather than the more erratic conditions encountered in a live fire.

Of those researchers who experimentally investigated TEG integration into a working stoves, Killander and Bass [9] were some of the earliest. In their study in an isolated home in northern Sweden, a thermoelectric generator was connected to a wood-fed stove. Using two Hi-Z HZ20 modules cooled by a 12 V, 2.2 W fan, their prototype was capable of producing up to 10 W in the cold mornings, with 4~7 W produced as the house became warmer during the day. The output voltage from the TEGs was boosted to 13.5 V by a DC/DC converter and the generated power was sufficient to operate the cooling fan and charge four 6 V batteries. These batteries were connected in series/parallel to maintain a 12 V output to provide some electric light and supply some television during the night.

Sawyer et al. [10] designed a thermoelectric module coupled with a Haitian cooking stove. The primary intention was to increase the efficiency of the stove by rerouting the TEG cooling air to the combustion chamber. The minimum requirement of the generator was to power its own cooling fan. The authors also intended to charge a battery pack which would allow the fan to run at start-up without TEG power, and to charge a secondary battery pack that would be able to power devices connected via USB A Taihuaxing module TEP-1264-1.5 was used which could produce up to 4 W at a temperature difference of 200 °C. It was discovered that halving the flow rate of air into the combustion chamber had minimal effect on the time to boil 2 litres of water, but noticeably affected the cooling of the TEG. Indeed, the design relied on the fan running at the maximum flow rate at all times. In their experiments the desired temperature differential of 200 °C could not be achieved due to rising cold side temperatures. The authors determined that the main issue with the system was how the limited power provided by the thermoelectric module was budgeted between the components and loads.

Champier et al. [11, 12] investigated using the exhaust gases stream from an energy efficient mud cooking stove as the heat source for a thermoelectric generator. An experimental rig was setup initially using a 2.2 kW butane gas burner. Using four bismuth telluride thermoelectric modules (Taihuaxing Co. Ltd TEP1-12656-0.8, max. 10.5 W at matched load) the authors obtained between 1.7 W and 2.3 W per module at an approximate module temperature difference of 160 °C and a total of 7 W was generated. Citing the clamping pressure as one of the main reasons for the low power output, the authors made improvements to the generator design in what was called the “TEGBois II” and included a fan to replicate the gas temperatures and flow speeds in the stove. With a moving airstream at approximately 400 °C and maximum power point optimisation of the DC-DC power conversion [13], the authors obtained much improved power output and an energy efficiency for the electrical conversion of over 90%.

Goudarzi et al. [14] designed a multifunction device capable of producing a considerable amount of electricity as well as hot water. The prototype stove was equipped with baffles and a post-combustion chamber which ensured more complete burning of the exhaust gases by returning them to the hottest part of the firebox. At low stove temperatures, combustion was aided by a 1 W fan to aerate the fire. 21 thermoelectric modules (TEP1-12656-0.6) were used, each one connected by its hot side to a 50 mm-long aluminium piece which in turn was attached to the stove body. In this way the upper temperature limit of the TEGs was not exceeded. The modules were divided into seven groups of three, each connected electrically in series. Each TEG was cooled via a water-filled aluminium block, through which the water flow rate could be adjusted. The authors tested in an open environment and experimented with different fuel consumption rates, ultimately producing an average of 7.9 W for each module when charging with 9kg firewood per hour.

Raman et al. [15] described the development, design and performance analysis of a forced draft clean combustion cookstove powered by a single thermoelectric module capable of producing 5W at matched load. The power produced by the TEG was to power the blower to provide a clean combustion and reduce indoor air pollution. Since the authors obtained a maximum of 4.5W from the TEG and less than 1W was needed to power the blower, the remaining power was used for mobile phone charging and LED lighting.

Recently, the present authors described the design, laboratory testing, and field trial testing of an electricity producing cooking stove [16, 17] along with the development of appropriate charge control circuitry [18]. Results are discussed in the context of laboratory tests with the view of verifying the efficacy of the technology and provide a context within which actual use in field trials can be assessed. Ref. [17] outlined the deployment and preliminary results of a field trial, whereby five stoves with TEG generators and five without were equipped with data logging equipment and use behaviour was monitored for 80 days. This paper focussed primarily on behavioural aspects of the field trial participants including energy supply and demand. Here it was found that the technology was used as intended and provided sufficient, if not an abundance of electrical energy that was used by the participants to charge phones and LED lanterns for the duration of the field trial.

Many of the studies described above have application in the developing world. Including these studies, there still exists little information in the literature regarding the long or even short term performance of cooking stoves fitted with thermoelectric generators when used by the people they are designed for. Typically, laboratory and field performance will differ, and one can be confronted with problems in the field that were unforeseen or never encountered in a laboratory setting. This research aims to address some of the unknown issues with the help of rural communities in Malawi: for example, it is unknown how long rural villagers in Malawi use their cooking stoves each day. Including a TEG generator could alter their normal behaviour. Another question that must be addressed is the cost and quantity of energy necessary to make a meaningful impact on the lives of the target beneficiaries [19, 20]. Much of the information to date on these topics has been gathered in survey form which may be, in some cases, unreliable. Yet accurate information of this kind is crucial to adequately design a TEG-stove that meets the basic user requirements. Using the approach adopted in this study, it is possible to obtain quantitative rather than qualitative data on TEG-stove performance and usage.

This study is the third and final of a series of papers starting with the current TEG-stove design concept [16], its use in a field trial and subsequent participant behaviour [17] continuing now to a more focussed analysis on the thermal and energy performance characteristics of the TEG system itself during the field trial. It is envisaged that this work will inform those who are contemplating similar thermoelectric technologies for developing world applications.

1.2 Stove selection

In terms of fuel consumption and efficiency, the chitetezo mbaula cooking stove is an improvement of up to 43% on the traditional ‘three stone fire’ method of cooking [21]. Concern Universal Malawi has been involved in the production and marketing of nearly 20000 chitetezo stoves since 2008 [16]. This stove was selected for integration with the TEG generator because of its familiarity within the rural communities, and also because its portability presented a technical and design challenge. Recently, the government of Malawi committed to introducing two million cleaner cooking stoves nationwide by 2020 [22].

2. Overview of Thermoelectricity

Thermoelectric generators, or TEGs, are solid state energy devices which convert heat directly into electricity by means of the thermoelectric effect. An overview of thermoelectricity is provided by Rowe [23], and Hodes [24]. One of the problems encountered when predicting TEG module performance is that the theoretical material properties are typically better than the practical ones. The model adopted in this study is described in detail in [16] and [18] and uses the method employed by Hsu and Huang [25]. This method, known as the effective Seebeck coefficient model, calculates the parameter α under zero load (i.e. open circuit condition), but also imposes realistic temperature and pressure conditions to the module to assess its behaviour in practical scenarios. This is necessary since the TEG performs differently under load conditions, and this model improves significantly upon the standard model which requires detailed knowledge of the internal geometry of the TEG. The effective Seebeck coefficient, α_{eff}, is calculated by applying a fixed temperature difference across the TEG and varying the load resistance. The power is obtained from Equation 1.

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

Theoretically, maximum power is obtained when the TEG resistance matches the load resistance; i.e. when $R_{TEG} = R_L$. Some specifications for the thermoelectric module used in the field trial are provided in Table 1.

Table 1: TEG1-12610-5.1 supplier specifications

Dimensions	40mm x 40mm
Open circuit voltage	8.4 V
Internal resistance	3 Ω
Match load output voltage/current	4.2 V / 1.4 A
Match load max. output power	5.9 W
Heat flow through the module	~ 140 W

The TEG is used as a power source to power its own cooling fan and to charge in parallel 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 2.

Table 2: $LiFePo_4$ battery specifications

Cell dimensions (mm)	ϕ 26 x 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	>1,000

3. Generator & electronic circuit design

The stove is estimated to produce 3 kW, of which an estimated maximum 140 W is extracted for the generator. A visual inspection of the stove is performed before a fire is created in the stove to check for cracks during thermal expansion. To install the generator, a hole is made in the side wall of the stove. 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 noticeably weaken or damage the stove. From this point onwards the term ‘generator’ refers to the whole system: heat collection, TEG and cooling.

3.1 Heat collection and dissipation

The TEG is located between two 50x50x3 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 is a second copper plate, out of which three copper rods protrude into the combustion chamber. The rods deliver heat to the TEG, but are primarily intended to be used as a grate to aid combustion by allowing air to be drawn into the stove under and up through the fuel.

The copper plate on the cold side of the TEG is thermally connected to a commercially available heat pipe heat sink, normally used in CPU cooling (Arctic Cooling Freezer 13). This heat sink consists of four u-shaped 6 mm diameter copper heat pipes and 45 aluminium fins. The 92 mm diameter fan supplied with this heat sink operates at 12 V and consumes up to 2.2 W of electricity which is 37% of the maximum power that the chosen TEG can produce at a cold side of 80°C. Instead, the impeller from this fan is dismantled from the motor and connected to a low power DC motor which can run the fan from 0.3 V and consumes typically up to 0.5 W since the circuit voltage rarely exceeds 5 V. Since the fan will begin to rotate from very low TEG voltages, it eliminates the necessity to charge a battery pack which would allow the fan to run at start up without TEG power, a problem encountered by Sawyer et al. [10]. The cooling capacity of the fan is somewhat reduced, but adequate cooling can still be achieved with a much lower power drain as shown in Figure 1.

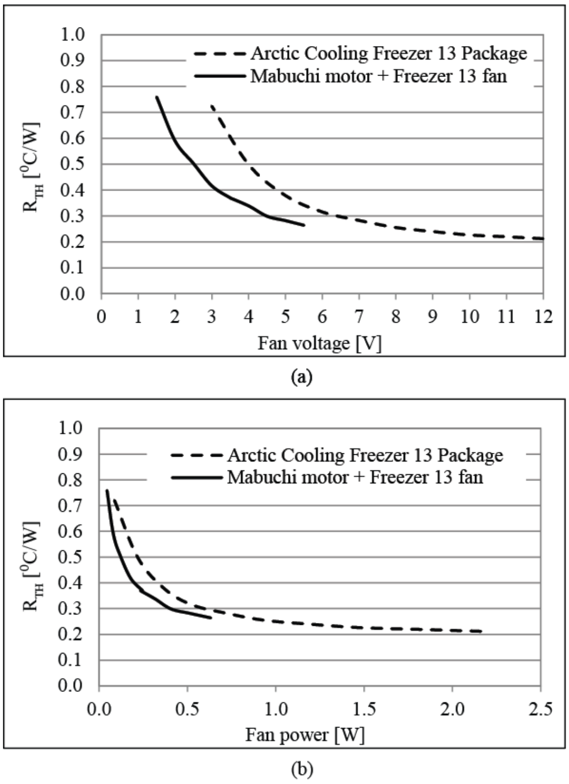


Figure 1: Thermal resistance of Arctic Cooling Freezer 13 heat sink with 100 W heat input versus (a) fan supply voltage and (b) fan supply power

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 module from direct exposure to the fire. A sketch and photograph of the generator assembly is provided in Figure 2. Thermally conductive paste is used at each contact face to reduce contact resistances. The integration with the stove is provided in Figure 3.

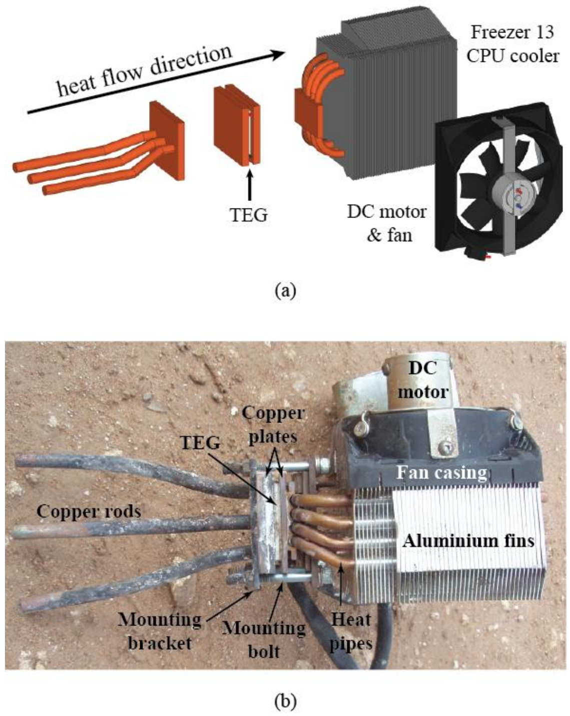


Figure 2: Heat collection and dissipation design

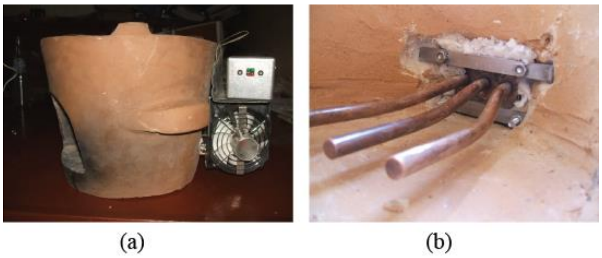

(a) (b)

Figure 3: Integration of generator with chitetezo mbaula: (a) outside view and (b) inside the stove

As mentioned previously, the TEG is positioned between two copper plates. The clamping pressure affects the electrical output. For example, in their laboratory experiments Rinalde et al. [8] found that in some cases there was a 100 % change in output power with increasing clamping pressure. At an apparent TEG temperature difference of 200 °C, their TEG output was 35% below the value claimed by the manufacturer. Increasing the pressure on the TEG should, in theory, decrease the contact resistances and reduce the difference in apparent and actual temperatures across the TEG, as shown in Figure 4.

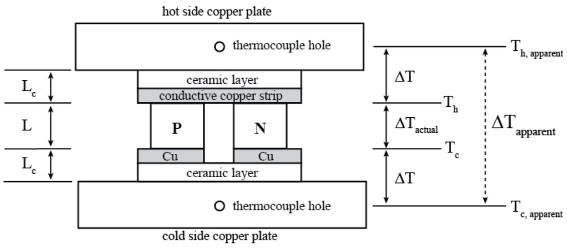


Figure 4: Apparent and actual temperatures across the TEG

The pressure must be applied evenly on both sides of the thermoelectric module. Slight pressure variations across the surfaces are enough to crack the brittle ceramic layer. Since the thermo-elements are connected electrically in series to provide the output, the device cannot usually withstand the breakage of even a single thermocouple. For the TEG module used in this study, a clamping torque of 1 N·m per 50mm M5 bolt was used.

3.2 Battery charging circuitry

The power produced 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 quite simple, and has been specifically designed to be so. Several researchers such as [26-28] have investigated maximum-power-point-tracking (MPPT) techniques to ensure that the load resistance and internal resistance of the TEG are matched at all times. However, previous studies using this simple 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 [17, 18], provided no external load is connected to the circuit. At these TEG temperature differences, the primary battery resistance and the internal resistance of the TEG are better matched and can result in output powers similar to that achieved using MPPT methods.

A circuit diagram is provided in Figure 5. The circuit includes the following features:

- 0.005 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.
- 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.
- A 3.9 V Zener diode prevents battery overcharge by bypassing the battery when the battery nears full charge. Unfortunately this particular Zener represents a significant power loss as it leaks current from voltages as low as 3 V.
- 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. Red LEDs indicate when the TEG voltage is sufficient to charge the battery. Green LEDs indicate full charge.
- A DC–DC converter boosts the output voltage to a more useful 5 V, and is connected to a single male USB port.

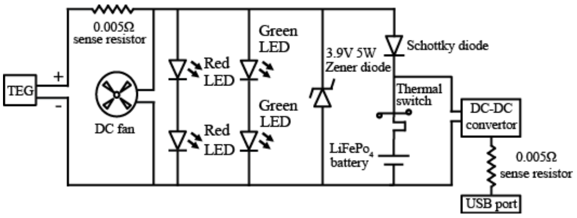


Figure 5: Primary battery charging circuit

3.3 Laboratory testing of TEG-stove performance

Several experiments were performed in a laboratory setting prior to the field trial [16]. The results from these experiments showed that the TEG could produce a power output up to 5.9 W when integrated with a stove, which is in agreement with the manufacturer's specifications. To produce maximum power from the TEG module used in this study, a TEG temperature difference of over 200 °C is required. In addition, the cold side TEG temperature should be as low as possible. Furthermore, maximum power is generated from a TEG only when its internal resistance matches that of the load.

Before the TEG-stoves were deployed to the field, it was necessary to investigate whether the inclusion of the generator affected the performance of the chitetezo mbaula. A series of water boil tests (WBTs) was performed in a controlled setting using both the normal stove and one with the TEG generator. In each experiment, an aluminium saucepan of water containing the same volume of liquid was brought to the boil. All tests started with 30g of wood kindling and 10g of tinder, all from the same wood source. All fuel to be added was weighed prior to the start of the experiment. The experiment consisted of 3 phases:

1. High power from a cold (ambient) start up
2. High power test from hot start up
3. Low power simmer

The following parameters were measured/calculated: time to boil, burning rate, thermal efficiency, specific fuel consumption and firepower. Results from these experiments showed that both stoves displayed a thermal efficiency of 18~20% and a firepower of 3.1~3.3kW when averaged over the three test phases. These values were repeatable over several experiments. There was no significant consistent deterioration or improvement in energy performance with the inclusion of the generator.

An estimated maximum 140 W of heat is extracted for the generator. There is likely also some minor heat losses due to the design. The thin sheet metal skirt included with the generator may offset these energy losses by limiting the heat transfer to the stove walls, as shown in [16]. Also, it must be noted that the WBT is not a perfect measurement of stove performance. Indeed one of the desired outcomes from field testing the TEG-stove is that users' perceptions on stove performance can be obtained.

3.4 Data acquisition during field trial

Each generator stove was equipped with data loggers which record the temperature in the stove wall and combustion chamber, the approximate temperature on either side of the TEG and the TEG voltage. Calculation of the TEG current and the current drawn via the USB was achieved by recording the voltage drop across two 0.005 Ohm sense resistors. All data loggers recorded for the entire duration of the trial at the selected recording rate of one reading per minute.

4. Results & discussion

Five generator stoves were deployed in Malawi to the 'treatment group' village of Mponda, Balaka. A further five 'control group' stoves without TEG generators were deployed in the nearby village of Dulani, Balaka. The control group was used to assess if there was a significant difference in stove usage behaviour between those with a TEG-stove and those without. Nine stoves remained logging in the field for up to 80 days.

4.1 Stove usage

There exists little quantitative data on cooking stove and fuel usage in the developing world. A potential negative side effect of TEG-stove generator is that the users may increase their normal stove usage to produce electricity. This is not due to excessive amounts of heat being removed; rather the users' perception that burning more fuel leads to more electricity. It was stressed to the users that electricity would be produced under normal operating conditions but inevitably there would be some behavioural alteration, if only at the beginning of the trial. Unfortunately, no prior information was available on the typical stove usage for the participants in this study, although this will be rectified in future studies.

Figure 6 plots the usage for both the treatment and control groups. To identify 'usage', the data recorded by the combustion chamber thermocouple is analysed. If the thermocouple reading is above 100 °C, the stove is deemed to be 'in use'. This value was chosen because at this hot side temperature the TEG begins to generate notable power. It is unknown if the field trial participants were actively tending to the stove however, or indeed if they were operating it for a specific purpose. However, since the temperature in the combustion chamber at the thermocouple location drops very quickly when fuel is not being burned, Figure 6 at least indicates the length of time the participants burned fuels in the data-logged stoves.

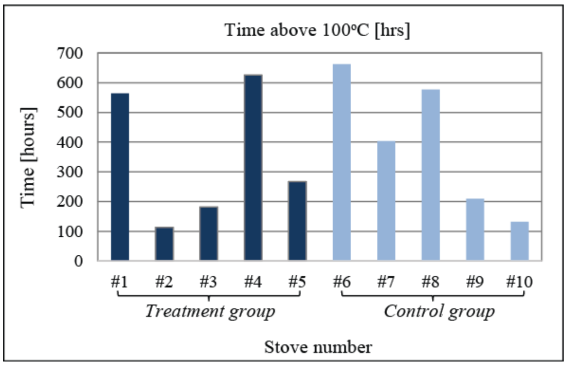


Figure 6: Stove usage during the field trial

The figure plots the total number of hours above 100 °C for all stoves. Interestingly, two stoves from each of the groups are used more frequently, and indeed a control group stove displays the most usage. Although the sample number is too small to make generalisations, it would appear that prolonged stove usage is normal and not merely due to the inclusion of the generator. For example, it has been shown that some control group participants used the stove for up to 18 hours on a particular day, with average usage never lower than 4 hours per day [17]. Nevertheless, for a true indication of the effect of the TEG-stove generator on user behaviour, a pre and post-intervention study should be performed.

It was also noted by Concern Universal field facilitators that many participants had more than one stove, sometimes operating two or more at the same time. These stoves may also have been of different type, as users tend to have a preference for a particular stove based on their cooking needs (e.g. second stoves used just for boiling water were observed). Table 3 and Table 4 display the total amount of days during which the supplied stoves were not in use.

Table 3: No. of days TEG-stove is not in use

Stove	#1	#2	#3	#4	#5
Total	5/80	13/30	33/80	1/80	22/80
% of days	6.3	43.3	41.3	1.3	27.5

Table 4: No. of days control group stove is not in use

Stove	#6	#7	#8	#9	#10
Total	0/77	20/77	0/77	25/77	41/77
% of days	0	26	0	32.5	54.3

Figure 7 displays the erratic usage of stove 4 as an example. This behaviour is typical of all stoves in the study, and reinforces the likelihood that other cooking stoves are used, and that cooking times will likely vary depending on food types. It was feared that TEG-stove usage may drop off after the initial excitement of having a new technology but this appears not to be the case. Stove usage varied for all stoves - both in the treatment and control groups - throughout the field trial.

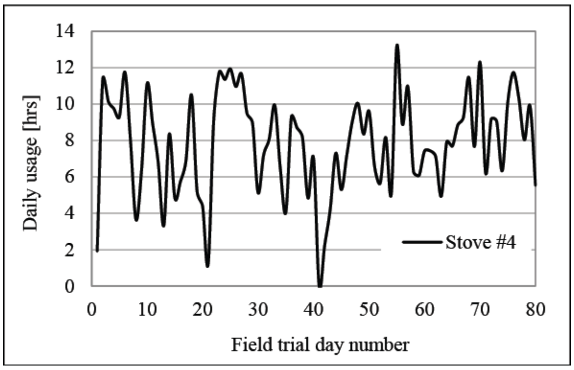


Figure 7: TEG-stove 4 usage during field trial

4.2 TEG temperatures during trial

Prolonged stove usage could have an effect on TEG performance, particularly on its life cycle if the TEG experiences frequent, large temperature cycles during the day. Mastbergen [29] describes the thermal stresses which can cause fatigue and ultimately cracking or separation of the interface between the thermo-elements and the conductive strip. This leads to an increase in electrical resistance, sometimes after just a few hundred cycles.

The chosen TEG in this study has a maximum continuous operating temperature of 270 °C, with intermittent cycling up to 300 °C allowed. Figure 8 plots the maximum hot and cold side temperatures and the maximum TEG temperature difference that occurred during the field trial. Only TEG-stove 2 greatly exceeded 300 °C during the trial and this is discussed in a separate subsection.

Table 5 shows that two other TEG-stoves only briefly exceeded the maximum recommended hot side temperature, meaning that the generator was well positioned to limit the hot side temperature. The temperatures recorded by the thermocouples are likely different to the actual temperatures across the TEG's thermo-elements (cf. Figure 4 previously).

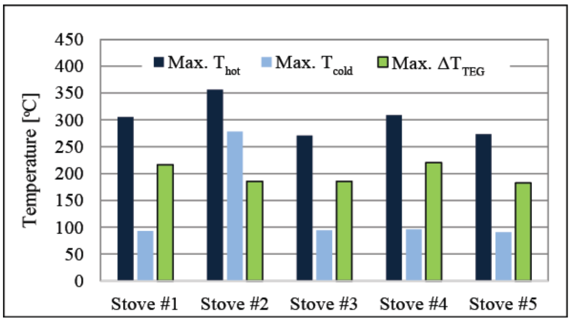


Figure 8: Maximum apparent TEG temperatures

Table 5: Time TEG hot side was above 300 °C

Stove	#1	#2	#3	#4	#5
Total [mins]	3	301	0	5	0

Ideally, the TEG would operate continuously at 270 °C hot side with the cold side temperature as low as possible but this is not realistic for the given design. The temperatures in Figure 8 represent the maximum readings over the whole trial, whereas Figure 9 displays the average of the daily maximum temperatures. This provides an indication of how often the generator approached its ideal operating point. TEG-stoves 1, 2 and 4 had average maximum daily hot side temperatures of almost 250 °C, while stoves 3 and 5 were slightly and considerably lower respectively. The hot side temperature is obviously affected by the fuel type, presence of flames and stoking methods, but also by the location of the generator in the stove. Small changes in the distance measured from the centre of the stove to the TEG can have a significant impact on the hot side temperature. For example in this design, fixing the generator 15mm further away from the centre of the stove resulted in a 30 °C reduction. In an attempt to achieve consistency in the stove manufacturing process, paddle moulds are now being used by the stove making groups in Malawi. It is conceivable that the hole for the generator could be incorporated at this stage, which would allow for greater accuracy and consistency in the positioning of the generator.

Returning to Figure 9, in all cases the average of the daily maximum cold side temperature was less than 100 °C. This temperature limit is significant as it may be a limit for any potential passive water-based cooling solutions. Clearly, to justify the use of a power draining fan-based approach, the cooling system must be capable of lowering the cold side temperature below 100 °C.

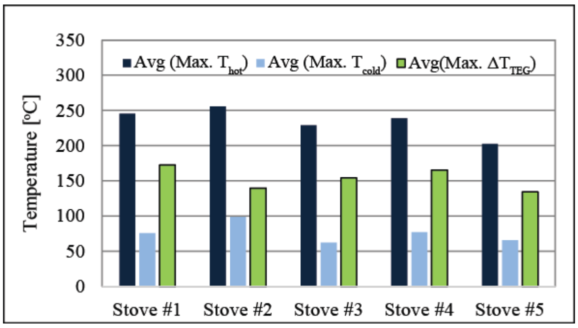


Figure 9: Average of maximum TEG temperatures

The figure also plots the average maximum TEG temperature difference. As mentioned previously, this circuit achieves close to the maximum power point from $\Delta T_{TEG} \geq 150$ °C. From the figure, three of the five TEG stoves appear to reach this value regularly. It must be noted that it is still desirable to have the same ΔT_{TEG} at a lower cold side temperature as this will produce more power. The cold side temperature is affected by heat exchanger fouling due to food spillage as seen in Figure 10. This was noticeable upon field visits during the trial and upon data collection at the end of the trial period.

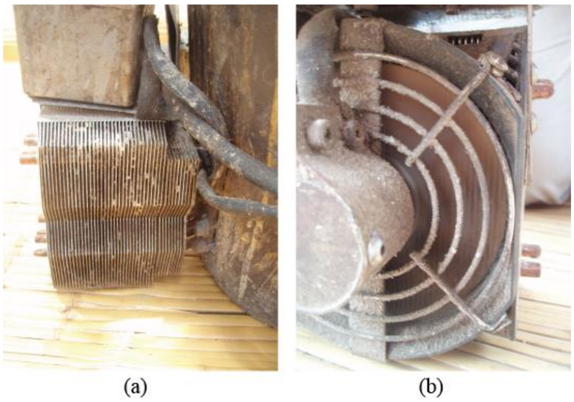
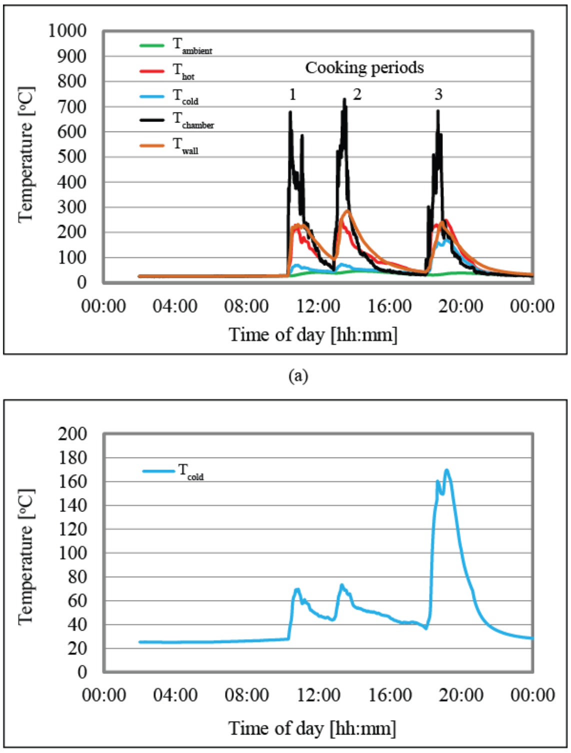

(a) (b)

Figure 10: Fouling of (a) the heat sink and (b) the cooling fan

4.2.1 Failure of TEG-stove 2

From Figure 8 it can be seen that TEG-stove 2 exceeded 350 °C on the hot side, which was as a result of this stove failing during the field trial. The point of failure occurred on the 31st day of the field trial during the third usage period of the day as seen in Figure 11. The reason for the malfunction was heat sink failure (see Figure 12). The temperature of the cold side of the TEG rose to approximately 150 °C on this day. Interestingly, it was not caused by excess heat flow through the TEG since the hot side temperature of the TEG was only just above 200 °C at the time. The failure was due to the breakdown of the heat exchanger solder at the contact point between the heat pipes and their base plate. This meant that the heat transported through the TEG could not pass to the heat exchanger effectively, which ultimately caused overheating of the TEG until failure occurred. The cooling fan and circuit have subsequently been tested and operated as normal which reinforces the idea that the failure was purely mechanical.



(a)

(b)

Figure 11: TEG-stove 2 temperatures on day 31, showing (a) the three cooking periods and (b) the rise in cold side TEG temperature during the final cooking period.

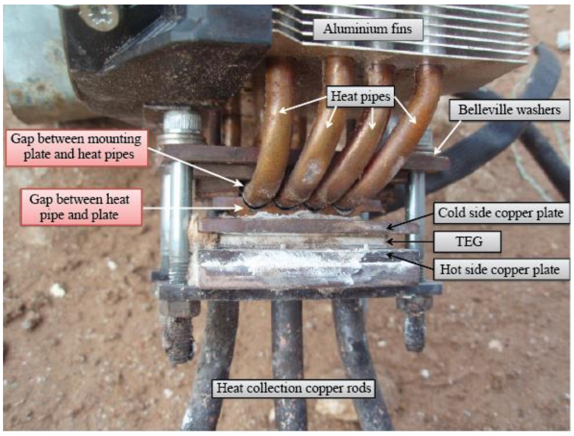


Figure 12: TEG-stove 2 malfunction due to failure of the solder connection of the heat pipe base

The cause of the solder breakdown is likely due to how the generator was mounted to the stove. The mounting bolts apply pressure on the heat pipes, while the clamping of the TEG applies pressure on the plate the heat pipes are soldered to. This soldered connection is therefore the weakest link where mechanical failure can occur if the generator is accidentally knocked or dropped. Unfortunately, using this heat sink means that the generator protrudes significantly from the stove wall. TEG-stove 2 was replaced by a new, non-data logged stove generator for the remainder of the trial and operated without problems.

4.3 TEG real-life performance

Figure 13 displays the maximum output power generated by each TEG-stove during the 80 day field trial. Due to the high ambient air temperature and increased sunlight exposure in Malawi it was expected that power generation would be less compared with experiments performed in Dublin. Despite this, four of the five generators produced near to or more than 5 W which shows that the generators could perform reasonably well under real life conditions.

The figure also plots the average of the daily maximum power generated by each TEG-stove. Stoves 1 to 4 approached 4 W regularly whereas stove 5 produced less than 3 W of power. This can be linked to the temperature plots in Figure 9 where it was shown that stove 5 had an average daily maximum hot side temperature of only 200 °C, with an average daily maximum $\Delta T_{TEG} \approx 130$ °C. This indicates that the field trial participants are not regularly creating the conditions to generate the maximum achievable power from the generators. From observations made in the field and comments from the field facilitators, it is noted that users regularly leave the fire unattended which could account for the power deficit.

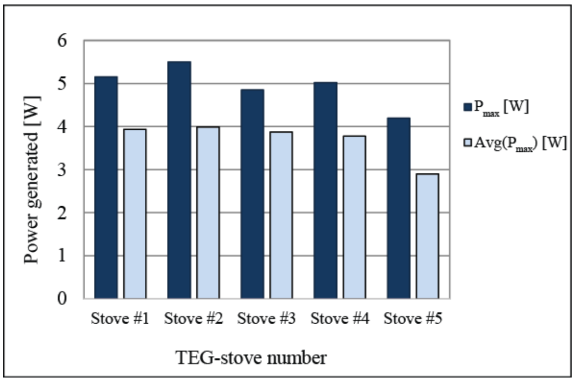
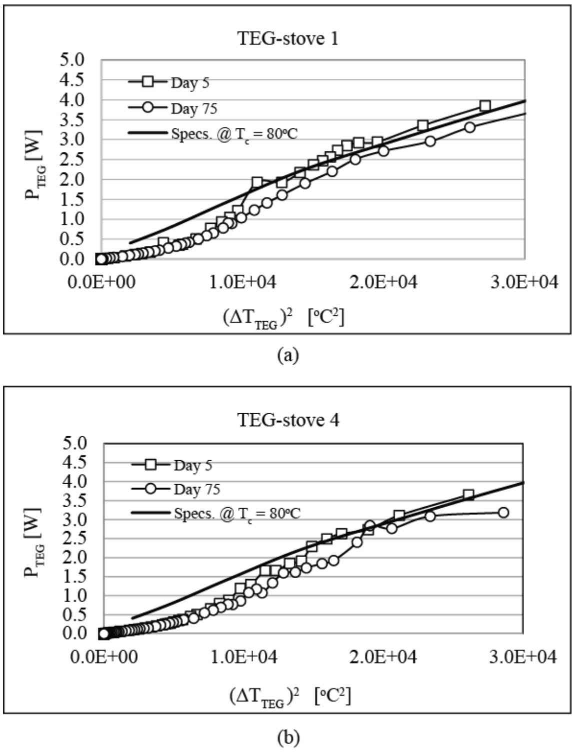


Figure 13: Maximum and average maximum power generated by each TEG-stove during the field trial

To establish if TEG output deteriorated over time, the power generated for each TEG was studied at the beginning and end of the field trial. For TEGs, output power is proportional to the square of the temperature difference. Figure 14 plots this comparison for TEG-stoves 1 and 4 which were the most frequently used stoves. Also in the figure is data corresponding to the manufacturer's specifications for this TEG when the cold side is maintained at 80 °C. The reason for not pursuing a MPPT technique can be seen. At larger temperature differences the power output from the TEG is close to the manufacturer's specifications, though at lower temperatures the output power is less than optimum as the load is not matched to the internal resistance of the TEG. This is discussed further in ref. [17]. From the figure there appears to be a small decrease in output power over time for both generators. The cause of this decrease is not merely due to thermal cycling of the TEG itself, rather its effect on the generator system as a whole. In particular, thermal cycling seems to cause a pumping effect and eventual drying out of the thermal paste. There can also be noticeable loosening of the clamping nuts which reduces clamping pressure and power output. This behaviour was also noted by Mastbergen [29], but it is important to note that these issues could be remedied with simple maintenance by trained personnel.



(a)

(b)

Figure 14: TEG power output over time for (a) TEG-stove 1 and (b) TEG-stove 4

4.3.1 Direct -vs- primary battery charging

Efficiency is defined as the power output to the load relative to the power generated by the TEG. Due to the power consumed by the fan, Schottky and Zener diodes and other circuit components, approximately 60% of the power generated from the TEG can be stored in the battery when no external load is connected to the USB port, though the charge level of the battery does have an impact on this figure [16]. The field trial participants were provided with a USB cable and an LED lantern as well as multiple connectors for mobile phones. In the interests of safety, and particularly because small children are frequently with the stove users, it was recommended to the participants that they charge when the stove was not in use, i.e. to use the energy stored in the primary battery. Understandably, the users charged at their convenience and the results in Table 6 highlight this.

Table 6: Electrical power usage behaviour

Stove	#1	#2	#3	#4	#5
Charging time during stove use [hrs]	25	0	66	39	30
Charging time from battery store [hrs]	72	19	23	37	38

Since many of the participants charged while using the stove, it raises interesting questions about the necessity of the primary battery since it increases the overall cost of the system. Indeed, the user of TEG-stove 3 said she valued the TEG-stove so highly that she mainly cooked with this stove only when she needed electricity, for fear of overusing the stove and breaking it. This is reflected in **Error! Reference source not found.** which shows frequent gaps between power generating periods.

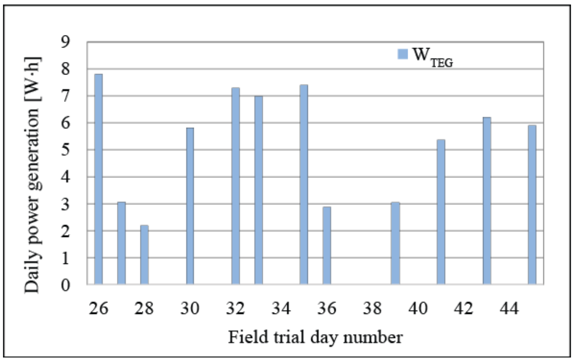


Figure 15: Subset of TEG-Stove 3 daily power generated showing irregular usage

Figure 16 highlights that the power generated was immediately consumed by the user and therefore the connected device was charged primarily from the TEG directly. On some occasions the consumed power exceeded the power generated. In these cases, some of the energy stored in the primary battery during previous burning periods was also used to charge the appliance. An example of this behaviour can be observed when a user connects a device to the USB port during the evening cooking period. The device charges while cooking but remains connected when cooking has finished. At this point the energy stored in the primary battery during the morning and afternoon cooking periods will continue to charge the device.

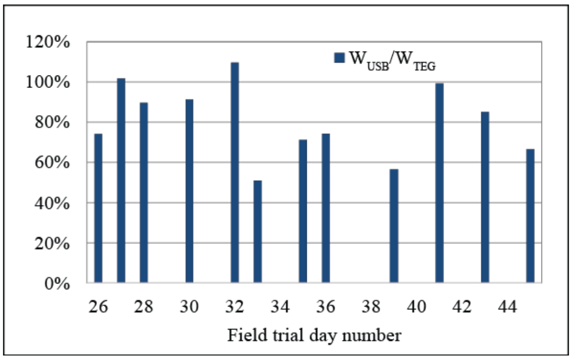
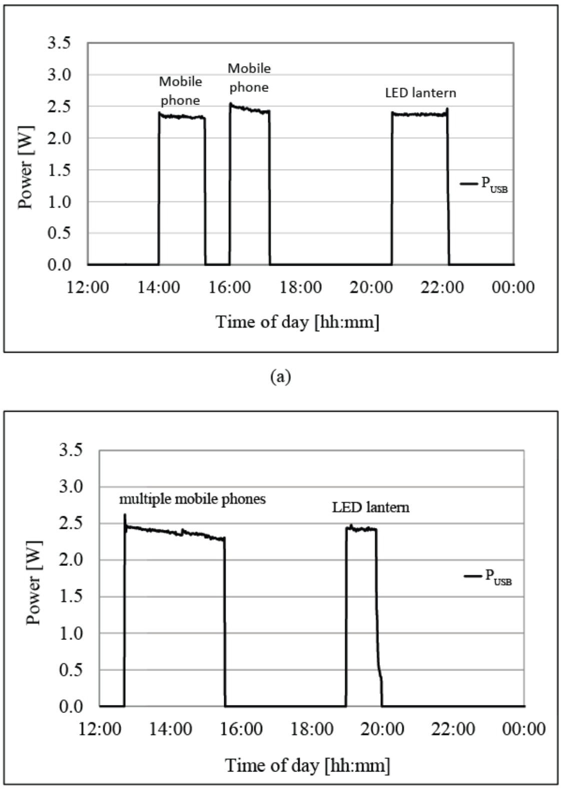


Figure 16: Subset of TEG-Stove 3 daily power consumption as a percentage of generated power

4.3.2 Appliance charging

Field facilitators and user surveys showed that the participants charged the provided LED lights, mobile phones, and even radios using the TEG stove. In some cases, phone charging was used as an income generating activity. Power consumption behaviour, like stove usage, was erratic. Users may go days without charging an appliance and then suddenly charge several in a 24h period. By analysing the power consumption profiles, it is sometimes possible to ascertain the devices charged. Figure 17 shows selected power consumption profiles for TEG-stoves 1 and 4. From these images it is possible to differentiate between mobile phone and LED lantern charging. Mobile phone charging with this circuit is characterised by an initial spike in current or power followed by a slow decrease over the charging period. The LED lantern, if charged from flat, typically maintains a constant charging power. From Figure 17a, the user of TEG-stove 1 was able to charge two mobile phones and the LED lantern on this day. Similarly, the user for TEG-stove 4 was also able to charge two mobile phones and the LED lantern, although the charging profiles are quite different. During the first charging profile, it is likely that the user quickly disconnected the first phone and connected a second phone which would explain the extended charging time.



(a)

(b)

Figure 17: Selected power consumption profiles for (a) TEG-stove 1 and (b) TEG-stove 4

4.3.4 Supply –vs– demand

The total power generated and consumed by each stove user is given in Table 7. The user of TEG-stove 3 has a well-balanced power profile because direct charging was frequently employed. Indeed it would seem that efficiencies greater than 60% can be obtained when direct charging. This is because the TEG and accompanying circuit approach the maximum power point at a temperature difference above 150°C, but below this the battery resistance does not match the TEG's internal resistance. When another load is connected to the circuit via the USB port, in some cases the internal and load resistances are better matched and the TEG produces more power than it would when charging the primary battery only.

For the other TEG-stoves, power generation significantly exceeded power consumption. The largest average daily power consumption was just over 3 W·h for TEG-stove 1 [17]. This would suggest that 3 W·h is sufficient to meet the daily electrical needs of a rural household in this region.

To put the power consumption into context, consider just the ability to provide light. The LED lantern provided was shown to require 4 W·h to charge from flat. This was sufficient to provide a total of 10 hours of light (5 hours in turbo mode and 5 in lantern mode, see ref. [16]). If the power consumed by the field trial participants was solely used to charge the LED lantern, an equivalent lighting time can be estimated as shown in Table 7. The table also displays the estimated available lighting time per day based on power consumption measurements.

Table 7: Total power generated and consumed for each TEG-stove

Stove	#1	#2	#3	#4	#5
Power generated [W·h]	693	138	259	704	259
Power consumed [W·h]	259	36	195	179	117
Equivalent LED lantern charges	65	9	49	45	29
Equivalent Light [hrs]	650	90	490	450	290
Equivalent Light hours per day [hrs/day]	8.1	3	6.1	5.6	3.6

5. Conclusions

Five prototype TEG-generator cooking stoves were deployed to a village community in rural Malawi, along with five non-generating stoves. The TEG-stoves were successfully used by the participants to charge mobile phones, lights and radios. Of the five generators deployed, one failed due to mechanical breakdown on the cooling side.

Stove usage behaviour was determined to be erratic. Prolonged stove usage is not solely attributable to the inclusion of the generator, since the longest usage periods were found in the control group who did not have TEG-stoves. Temperature analysis showed that the majority of the TEGs were kept within their recommended operating conditions for the vast majority of the trial, although the effect of thermal cycling seemed to cause a small decrease in output power over time.

In terms of power production, the users did not frequently obtain the maximum power output from the generators, yet the power generated greatly exceeded that consumed in most cases. It would appear from the daily power consumption profiles that 3 W·h is sufficient to meet the average daily electrical power requirements for the participants in this study. The generator design has been refined based on the results of this study with a view to a second field trial.

Acknowledgments

The authors would like to gratefully acknowledge Irish Aid, The Irish Research Council and Intel Corporation for their support and contribution to this research, and also Concern Universal for their continued assistance in the field.

Nomenclature

Symbol	Description	Unit
L	Length of thermo-element	m
L_c	Contact layer thickness	m
P_{elec}	Electrical power	W
P_{TEG}	Power generated by the TEG	W
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	K
T_c	Module cold side temperature	K
ΔT_{TEG}	Module temperature difference	K
ΔT_{actual}	Actual TEG temp. difference	K
$\Delta T_{apparent}$	Apparent TEG temp. difference	K
W_{TEG}	Power generated by the TEG	W·h
W_{USB}	Power consumed by user via USB	W·h
α	Seebeck coefficient	V/K
α_{eff}	Effective Seebeck coefficient	V/K

References

[1] OECD/IEA. Energy Poverty: How to make modern energy access universal? 2010.

[2] Codecasa MP, Fanciulli C, Gaddi R, Gomez-Paz F, Passaretti F. Update on the Design and Development of a TEG Cogenerator Device Integrated into Self-Standing Gas Heaters. 2013:1-6.

[3] Codecasa MP, Fanciulli C, Gaddi R, Passaretti F. Design and development of a thermoelectric cogeneration device integrated in autonomous gas heaters. 9th European Conference on Thermoelectrics: Ect2011, 28-30 Sept 2011. USA: American Institute of Physics; 2012. p. 512-15.

[4] Doloszeski M, Schmidt A. The use of thermoelectric converters for the production of electricity from biomass. XVI ICT '97 Proceedings ICT'97 16th International Conference on Thermoelectrics, 26-29 Aug 1997. New York, NY, USA: IEEE; 1997. p. 607-10.

[5] Eakburanawat J, Boonyaroonate I. Development of a thermoelectric battery-charger with microcontroller-based maximum power point tracking technique. Applied Energy. 2006;83:687-704.

[6] Gou X, Xiao H, Yang S. Modeling, experimental study and optimization on low-temperature waste heat thermoelectric generator system. Applied Energy. 2010;87:3131-6.

[7] Hsu C-T, Huang G-Y, Chu H-S, Yu B, Yao D-J. Experiments and simulations on low-temperature waste heat harvesting system by thermoelectric power generators. Applied Energy. 2011;88:1291-7.

[8] Rinalde GF, Juanico LE, Taglialavore E, Gortari S, Molina MG. Development of thermoelectric generators for electrification of isolated rural homes. International Journal of Hydrogen Energy. 2010;35:5818-22.

[9] Killander A, Bass JC. A stove-top generator for cold areas. Fifteenth International Conference on Thermoelectrics Proceedings ICT '96, 26-29 March 1996. New York, NY, USA: IEEE; 1996. p. 390-3.

[10] Sawyer B, Masood F, Rugg J, Bird J, Gorevski T. Thermoelectric and fan system for cook stove. 2008.

[11] Champier D, Bedecarrats JP, Kousksou T, Rivaletto M, Strub F, Pignolet P. Study of a TE (thermoelectric) generator incorporated in a multifunction wood stove. Energy. 2011;36:1518-26.

[12] Champier D, Bedecarrats JP, Rivaletto M, Strub F. Thermoelectric power generation from biomass cook stoves. Energy. 2010;35:935-42.

[13] Champier D, Favarel C, Bedecarrats JP, Kousksou T, Rozis JF. Prototype Combined Heater/Thermoelectric Power Generator for Remote Applications. 2013:1-12.

[14] Goudarzi AM, Mazandarani P, Panahi R, Behsaz H, Rezania A, Rosendahl LA. Integration of Thermoelectric Generators and Wood Stove to Produce Heat, Hot Water, and Electrical Power. 2013:1-7.

[15] Raman P, Ram NK, Gupta R. Development, design and performance analysis of a forced draft clean combustion cookstove powered by a thermo electric generator with multi-utility options. Energy. 2014;69:813-25.

[16] O'Shaughnessy SM, Deasy MJ, Kinsella CE, Doyle JV, Robinson AJ. Small scale electricity generation from a portable biomass cookstove: Prototype design and preliminary results. Applied Energy. 2013;102:374-85.

[17] O'Shaughnessy SM, Deasy MJ, Doyle JV, Robinson AJ. Field trial testing of an electricity-producing portable biomass cooking stove in rural Malawi. Energy for Sustainable Development. 2014;20:1-10.

[18] Kinsella CE, O'Shaughnessy SM, Deasy MJ, Duffy M, Robinson AJ. Battery charging considerations in small scale electricity generation from a thermoelectric module. Applied Energy. 2014;114:80-90.

[19] Adkins E, Oppelstrup K, Modi V. Rural household energy consumption in the millennium villages in Sub-Saharan Africa. Energy for Sustainable Development. 2012;16:249-59.

[20] Manchester SC, Swan LG. Off-grid mobile phone charging: An experimental study. Energy for Sustainable Development. 2013;17:564-71.

[21] Malakini; M, Mwase; W, Maganga; AM, Khonj; T. Fuelwood Use Efficiency in Cooking Technologies for Low Income Households in Malawi. Middle-East Journal of Scientific Research 2014;19:1328-33.

[22] Embassy of the United States Lilongwe Malawi. 2 million Clean Cook-stoves in Malawi by 2020. 2014.

[23] Rowe DM. Thermoelectric power generation. Proceedings of the Institution of Electrical Engineers. 1978;125:1113-36.

[24] Hodes M. On one-dimensional analysis of thermoelectric modules (TEMs). IEEE Transactions on Components and Packaging Technologies. 2005;28:218-29.

[25] Hsu CT, Huang GY, Chu HS, Yu B, Yao DJ. An effective Seebeck coefficient obtained by experimental results of a thermoelectric generator module. Applied Energy. 2011.

[26] Ko Ko W, Dasgupta S, Panda SK. An Optimized MPPT Circuit for Thermoelectric Energy Harvester for Low Power Applications. 8th International Conference on Power Electronics - ECCE Asia, 30 May-3 June 2011. Piscataway, NJ, USA: IEEE; 2011. p. 1579-84.

[27] Xiaodong Z, Wenlong L, Jiangui L. Thermoelectric power generation with maximum power point tracking.

8th International Conference on Advances in Power System Control, Operation and Management (APSCOM 2009), 8-11 Nov 2009. Stevenage, UK: IET; 2010. p. 6 pp.

[28] Sungkyu C, Namjae K, Soonseo P, Shiho K. A coreless maximum power point tracking circuit of thermoelectric generators for battery charging systems. Solid State Circuits Conference (A-SSCC), 2010 IEEE Asian2010. p. 1-4.

[29] Mastbergen D. Development and optimization of a stove-powered thermoelectric generator: Colorado State University; 2008.