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Adaptive design of a prototype electricity-producing biomass cooking stove

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ABSTRACT

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

Introduction

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

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

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

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

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

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

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

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

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

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

Context of research and project objectives

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

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

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

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

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

TEG, battery and stove selection

Thermoelectric generators, or TEGs, are solid state energy devices which convert heat directly into electricity by means of the thermoelectric effect. For succinctness, a detailed explanation of thermoelectricity is not provided here. An excellent overview of thermoelectricity is given by Rowe (1978) and more recently by Hodes (2005). The model adopted in this study is described in detail in O'Shaughnessy et al. (2013) and Kinsella et al. (2014) and uses the 'Effective Seebeck Coefficient' method employed by Hsu et al. (2011), which calculates the Seebeck coefficient α under realistic conditions. The output electrical