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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 ($LiFePo_4$) 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.

Introduction

As discussed by 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. (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. (2010b). This has implications with regard to the environmental impact of cooking since it is related to CO_2, black soot and deforestation. For example, Venkataraman et al. (2010) state that 4% of India's CO_2 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 et al., 2010). Although there is still some debate regarding the relation between clean cookstoves, IAQ and health, Adkins et al. (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. (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 as the lowest in its population compared with emerging countries from other regions (Onyeji et al., 2012). In fact, most SSA countries were still using less than 20 W/Capita in 2005 (Mechtenberg et al., 2012) compared with developed countries, such as the USA who used around 2000 W/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 a country's

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Human Development Index (HDI). This situation is particularly prevalent in Malawi, where according to the WHO energy access report of 2009 (Gwénaëlle Legros et al., 2009), approximately 91% of the population has 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 the 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 be 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 the 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 USD), 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.

Review of TEGs and stove integration

In the literature there exists some work related to electricity generation from biomass cooking stoves in the developing world. Mastbergen (2008) and Mastbergen et al. (2005) developed and field tested a TEG-stove generator system with the objective of generating 45 W·h of electrical energy using two 14.7 W TEGs and a fan-cooled aluminium heat sink. The field trial results showed variable degrees of success and failure of the system, with the latter 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 (2007) investigated a TEG-stove system under laboratory conditions and was able to generate just under 2.5 W, 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. (2010) and Champier et al. (2011) developed a TEG generator for eventual use in biomass cookstoves in developing countries. Using heated gas to replicate the exhaust gas of a biomass cookstove their system was able to produce up to 7 W of electrical power from a single TEG rated at 10.5 W. 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. (2013) have developed a potential low cost cookstove technology with the capacity of generating in the region of 23 W 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 and 240 USD. They do discuss design changes for the stove and generator system which have the potential to reduce this cost in the region of 100 USD, though these have yet to be implemented.

Stove 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 (Fig. 1(a)) by replacing them with efficient and portable cookstoves. However, these cooking stoves can also have harmful social and environmental consequences if they are not culturally or environmentally sensitive.

As shown in Fig. 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.

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 whilst 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 mbaula 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 stone fire with new technologies due to social and cultural perceptions (Concern Universal, 2011). However, many development organisations such as Concern Universal feel that the added value of being able to generate electricity and potentially gain economic benefits from a chitetezo mbaula stove will provide the social and economic incentives to rural households to adopt improved cookstove technology.