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Full Length Research Paper

Microgasification cookstoves and pellet fuels from waste biomass: A cost and performance comparison with charcoal and natural gas in Tanzania

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Cooking with wood and wood charcoal is done by over 90% of Africa's population; it has two major challenges: deforestation and indoor air pollution from cooking smoke, the latter being the top risk factor for disease in Tanzania. Microgasification stoves (top lit up draft [TLUD]) that burn pellets produced from agricultural waste have potential to address both of these issues. We examined the relative efficiency and cost of the major urban cooking fuels - charcoal and liquefied natural gas (LNG) – and compared them to cooking with waste biomass-based pellet fuels; we also compared the performance of three models of natural draft (ND) TLUD stove (Troika, Jiko Bomba, St. John's) and one forced air (fan) stove (Philips). The Philips and averaged ND stoves used 83 and 133% more pellets by weight respectively to cook beans than charcoal, costing 47 and 93% more at 2013 charcoal and pellet prices. Cooking with LNG costs 387 to 647% more than cooking with charcoal, depending on gas flow rate. The high cost of LNG and LNG stoves will be barriers to the great majority of Tanzanians to move to this improved cookstove technologies (ICTs). Biochar production averaged 59 and 29% of total fuel in the ND and Philips, respectively. Interviews of 30 ND TLUD stove users showed that 60% abandoned use within one month, 80% stating that they produce too much smoke and 40% stating that controlling the air vent is too much trouble. Seventy five percent said that the TLUD cooks significantly faster than charcoal. Due to the continued 33-99% annual increase in charcoal prices in Tanzania, work on introducing TLUD stoves is justified.

Key words: Microgasification stoves, TLUD, improved cooking technologies, deforestation, pellet fuels.

INTRODUCTION

Cooking with wood and wood charcoal, done by 90% Tanzanians (Peter and Sander 2009) and 70% of Africa's population (Taylor and Nakai, 2012), presents two major challenges that require action: deforestation, and indoor air pollution from cooking smoke. Annual consumption of charcoal in Tanzania, nearly all for cooking, averages a drastically unsustainable 2 million metric tons, consuming the equivalent of 327,190 ha of forest/woodland per year (Kaale, 2014). Continued rapid population growth - Tanzania's population will double from its 2010 level by the year 2050 to 90 million (Rweyemamu, 2013), intensifies this issue. Indoor air pollution from cooking

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smoke has been found to substantially increase rates of acute respiratory infections, chronic obstructive pulmonary disease, lung cancer, tuberculosis, and asthma (Smith, 2000). Indoor air pollution from cooking smoke is the top risk factor for disease in Tanzania and is the third highest cause of premature death after HIV/AIDS and malaria (Horton, 2012). Programs are needed in the transition of households to improve cookstove technologies (ICTs) and in transition to more sustainable sources of cooking fuel such as waste biomass. A widespread grassroots transition to these alternatives will depend heavily on the cost of the ICT. Our research at St. John's University in Central Tanzania addresses both of these problems, fuels and stoves. In this paper, we examined the relative efficiency and cost of the major cooking fuels compared to waste biomass-based pellet fuels, as well as the performance of three models of biomass gasification cookstove, a class of stove with potential to replace unsustainable and unhealthy traditional cooking techniques.

There are three main groups of cooking fuels in Tanzania and much of Africa: 1) firewood, 2) charcoal, and 3) fossil natural gas and kerosene. Livestock manure, biogas, and biomass waste account for insignificant proportions in Tanzania (National Bureau of Statistics, Tanzania, 2013)[1]. Gas cooking is limited to the upper 0.5% of society (National Bureau of Statistics 2013) and is nearly all by liquefied natural gas (LNG) via portable gas tank. With 90% of rural households cooking with firewood, wood will for the foreseeable future be the primary fuel in rural areas, nearly all by 3-stone fire. ICTs that are specifically designed for firewood such as the Rocket Stove (Raman, 2013), which has a mouth on the side for progressively pushing in long pieces of wood and a combustion chamber that uses secondary air to efficiently burn emitted gases, can increase firewood efficiency and reduce smoke by 50% or more (MacCarty, 2010).

Charcoal is the primary fuel in urban and peri-urban Tanzania, used by 70% of households, and this sector is the focus of this paper. Charcoal cooking, done in simple perforated clay bowls, does not emit nearly the amount of smoke as 3-stone firewood cooking, generating less than 10% of the smoke ($PM_{2.5}$) as an equivalent 3-stone fire (Taylor and Nakai, 2012). Thus, our efforts to replace charcoal cooking with ICTs are driven primarily by the need to reduce deforestation.

A number of ICT introduction projects have been implemented in Tanzania, although there is no comprehensive recording or listing of ICT (or other types of) projects. Such projects can be locally active but unknown outside of the locale. It appears that most ICT introduction efforts address more efficient firewood cooking, such as the Maasai Stoves program (bioenergylists.org 2014) or the Tanzania Stoves Project of the Anglican Church (Emmanuel International UK 2014). Others have introduced more efficient charcoal stoves such as the EnviroFit stove, sold countrywide and tested in this research. At least two projects have introduced pellet-burning microgasification stoves along with pellet production – stove engineer Bjarne Laustsen's project introducing the Jiko Bomba stove (Roth, 2014), tested here; and a project based in Arusha run by TREE Ltd. (Treetanz, 2014). Other East African projects introducing microgasification stoves are: Inyenyeri Inc. in Rwanda, a ground-breaking social enterprise that makes available fan-driven stoves to its customers (Inyenyeri, 2014). In Zambia, the Swedish company Vagga till Vagga (Vaggatillvagga 2014) produces pellets from the massive amounts of sawdust generated from lumber production from tree plantations and offers microgasification pellet stoves to its customers. Awamu Biomass Energy in Kampala Uganda (Awamu Biomass Energy, 2014) makes available the Troika stove tested in this research.

The objective of this research was to evaluate the cost of cooking using various commonly used and potentially useful fuels in urban and peri-urban environments. These fuels consist: traditional (charcoal), fossil (LPG), and sustainable (pelletized waste biomass). Additionally we evaluated microgasification stoves designed for burning biomass pellet fuels, as well as an improved charcoal stove. If ICTs such as pellet systems are to be counted on to reduce demand for charcoal it is imperative that the cost and performance of each cooking technology be assessed. In this research we begin this process with a limited assessment of each of the major cooking technologies used in urban and peri-urban areas. ICTs for rural areas were not assessed, as these areas are not the major sink for charcoal, using mostly firewood.

Biomass densification for cooking fuels

Waste biomass, particularly from agriculture, holds significant potential to replace unsustainably produced tree-based charcoal. The current practice in most of Tanzania for waste and crop residue that cannot be used for livestock is to burn it in the field or at the processing site (that is, rice hulls). Most waste biomass is of insufficient density to be transported and used as cooking fuel in typical households and needs to be either a) shredded and densified into discrete pieces of minimum 1 cm^3 that allow pore space and air flow, or b) used in stoves designed for low-density biomass such as sawdust, wood shavings, rice hulls, maize cobs, livestock manure and tree litter. Some programs suggest that rural households should use dry livestock manure as fuel, as is common in India. A systems analysis is needed on this, as the nitrogen, phosphorus, and microbes in manure, which are lost and become pollutants in combustion, are valuable soil amendments in the perpetually nutrient deficient African soils (AGRA 2013). Biogas systems harvest both the energy and the nutrients from manure;

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[1] Statistics in the next two paragraphs are based on (National Bureau of Statistics, Tanzania, 2013) unless otherwise cited.

the carbon (methane) is utilized for cooking and the nutrients and microbes retained in ejected slurry that can be used as fertilizer.

Despite the cost of machine densification of waste biomass in terms of energy and capital investment compared to raw and hand processed fuels, this technology will likely play an important role in making profitable the transport and sale to urban areas of fuels made from waste biomass. Additionally, densification operations allow for the blending of sub-optimal with super-optimal biomass creating a relatively uniform fuel and achieving the optimal mix of components such as lignin and oil. Machine densification of shredded biomass is being done by two main technologies in Tanzania – pelletization and briquetting. We found that densification via hand-powered lever press (Hands on Engineering 2014) of a slurry of shredded biomass and paper produced a briquette of insufficient density for use in microgasification stoves, but which would be useful in Rocket stove types. Machine densification creates pressure and heat to melt lignin which acts as glue and gives a pellet or briquette that is approximately twice the density of hardwood (Roth 2014). Not all biomass contains sufficient lignin; therefore some feedstocks need a binder such as molasses to be added.

Pelleting technology uses a roller to press shredded biomass through a die plate with 100+ holes, creating the required pressure. Friction and steam from the moisture content of the feedstock creates the heat and pressure. Two problems with pelleting machines have been encountered in Tanzanian projects:

1) machines that were originally designed for pelleting feed grains were purchased for pelletizing woody and cellulosic biomass and failed to create sufficient pressure to make a dense pellet, and
2) the biomass mix becomes stuck in the die holes and each of the hundred or so holes periodically needs to drilled out by hand.

For this reason, at least one biomass densification project has transitioned to briquetting technology to produce stove fuels (Laustsen, 2014). All of the pelleting and briquetting machines are currently imported to East Africa. Hammer mills for shredding biomass are made in East Africa, and hand-driven shredder machine designs are available for local manufacture (Armstrong, 2007). The energy density of biomass pellets has been shown to be approximately: 27% of petroleum oil, 35% of mineral coal, 38% of ethanol, 146% of hardwood, 213% of softwood, 270% of wood chips, and 375% of sawdust (at moisture content of 4.5%, 10%, 15% for petroleum, pellets, and other biomass respectively) (Roth, 2014).

Obtaining cheap or free biomass for pellet production is important for keeping fuel costs low. The availability of waste biomass varies by region, and pellet production is best done in areas where agricultural and forestry productivity is high due to optimal rainfall. Best is to locate production near to where large amounts of pre-shredded waste biomass, such as sawdust, are generated. The Vagga till Vagga project does this in the copper region of Zambia. In Rwanda an innovative biomass sourcing model that has been developed by Inyenyeri Inc. is to incentivize rural households to deliver biomass to company hubs, where they receive credit for buying pellets and stoves. Our project in central Tanzania, a semi-arid, low-productivity region, is assessing the cost of using local biomass waste for pellet fuel vs. purchasing pellets from areas up to 500 km away where waste biomass is more readily available and pellets are inexpensive.

Microgasification stoves

Biomass gasification is a process of separating the heat-generated gases from the solid biomass for the purpose of controlling the burning of the gases (a fire wood is the burning of unseparated gases given off by the heated wood). Portable metal biomass microgasification stoves have been developed for the purpose of cooking in developing countries (Figures 2, 3, 4, 5) as well as for recreational use (Roth, 2014).

There are four stages in the microgasification stove combustion process after initial lighting of the biomass with a small amount of starter fuel such as kerosene:

1) biomass drying, in which water vapour is given off;
2) pyrolysis, in which temperatures over 300°C and limited oxygen from the primary air flow (Figure 1) generate energy-rich gases, leaving solid black carbon (char, also known as biochar);
3) Migration of the gases (also known as wood gases) upward to the second combustion zone which when mixed with oxygen (secondary air flow), combusts; and
4) char combustion and conversion to ash. This last stage can be interrupted and the char conserved as biochar for its soil amendment value.

Many biomass stove programs do not attempt to have their users stop char combustion for saving biochar due to the extra work and attention it takes. Biochar in the last ten years has emerged as a valuable soil amendment that enhances fertility and plant health (Reddy et al. 2013), particularly in tropical soils. Currently (2014) in Tanzania char of particle size below about 5 mm diameter, such as collects around charcoal sale sites, has no market value due to lack of awareness of its agricultural value.

Microgasification stoves control the flow of primary air to the solid fuel combustion area (Figure 1) such that pyrolysis and off-gassing occurs at an optimal rate; and then further control the secondary air input into the gas combustion zone such that all of the gases are burned and the cooking flame is clean as described in Roth

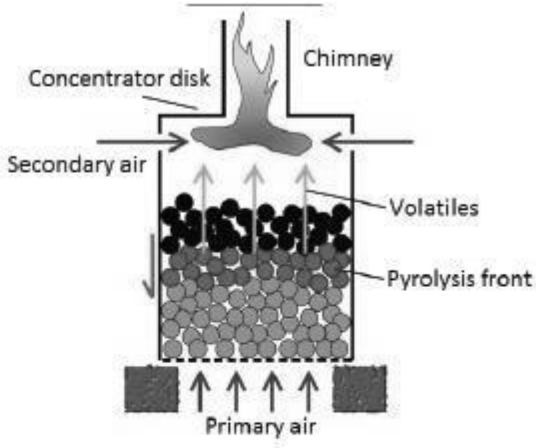

Figure 1. Elements of a TLUD (top lit up draft) microgasification stove. The pyrolysis front is shown here nearly midway through its migration downward through unburned fuel (From Roth 2014).

Figure 2. Troika (left) and Jiko Bomba TLUD stoves. Primary air vent can be seen at bottom of both.

Figure 3. St. John's (SJUT) stove.

Figure 4. Philips fan stove as advertised in Rwanda by Inyenyeri Inc.
Credit: Inyenyeri: A Rwandan Social Benefit Company

Figure 5. Charcoal stoves. Improved stove, left (Ecofit), traditional stove, right. Ecofit diameter is 31 cm.

(2014). As the combustion of pellets progresses, the pyrolytic zone migrates downward until all of the fuel has been converted to char. At this stage, the flame disappears and glowing char is seen and can be either emptied or extinguished in order to preserve the char as biochar, or it can be allowed to continue burning and producing heat for cooking.

The most common type of microgasification stove being developed worldwide and targeted for use in developing countries is the top-lit-up-draft (TLUD) stove, in which the top surface of the biomass fuel is lit and gases move upward from the pyrolytic zone. Dozens of models of TLUD stove exist. Some are simply designs for householders to build a stove from local materials such as discarded metal containers (also called tincanium stoves), others are designed for mass manufacture by local metal crafters, while others are sold as prefabricated assembly kits or are fully assembled and ready to use.

Fan-driven forced air (FA) versus natural draft (ND) appears to be the most important categorical divider of microgasification stoves. The fan and its power source drive up the cost of stoves and make these more challenging to introduce to low-income communities. However, the improved performance of well-designed fan stoves has been reason for at least one large scale biomass fuel enterprise in Africa to feature them as their primary cookstove (Inyenyeri, 2014). Thermo-electric generators built into stoves for charging the fan battery using the stove heat are increasingly common and overcome the problem of lack of electricity. However, households that lack electricity are less likely to be able to bear the increased cost of these technology-laden stoves.

International Organization for Standardization (ISO) standards are being developed for ICTs that will influence stove development and dissemination (Global Alliance for Clean Cookstoves, 2013). A tier system from 0 (3-stone fire) to 4 (satisfies strict health and environmental criteria) is currently being put in place (Partnership for Clean Outdoor Air 2012).

Socio-economics of cooking

Challenges, limited success, and outright failure have beset the hundreds of projects worldwide that have attempted to introduce improved cookstove technologies to the nearly half of the world's population who cook with solid fuels such as firewood and charcoal (Lewis and Pattanayak, 2012; Urmee and Gyamfi, 2014). Successful adoption of ICTs has been positively correlated with income, education, and urban location, a limited demographic worldwide. However, the development of "game-changing" conditions such as the rapidly increasing cost of traditional unsustainable fuels, the implementation of micro-credit programs, and a new generation of ICTs (such as TLUD technology) make for more optimism in the arena of implementing ICTs in the developing world (Lewis and Pattanyak, 2012). All three of these game-changing conditions currently exist or are developing in Dodoma and much of Tanzania.

At least one of Lewis and Pattanayak's (2012) criteria for successful ICT adoption, urban location, has significant potential in Tanzania, as nearly one third of the population of Tanzania is urban, with that proportion growing at 5% per year (National Bureau of Statistics, Tanzania, 2013). However, working against potential ICT adoption success is that the level of income and education of the vast majority of this population is low. The skyrocketing cost of charcoal along with foreseeable government enforcement of existing laws against tree cutting may drive change.

Charcoal is produced in rural areas from trees. The felled trees are cut into pieces, placed into a pit, ignited, and buried. Just enough air enters the pit to maintain combustion. This hypoxic combustion causes pyrolysis and off-gassing of non-carbon constituents such as water, nitrogen etc., leaving pure carbon (charcoal). The charcoal is put into 40-50 kg nylon/plastic bags and brought into cities and towns by truck and bicycle in an informal and often illegal system of trade. Cooking is generally done on a simple perforated clay bowl-shaped stove (Figure 5) that costs under US$5.

Tanzania has some of the world's largest reserves of natural gas, expected to reach over 5 trillion cubic meters, and investments in LNG development are substantial and growing (Daly, 2014). Whether this will translate to large-scale subsidised programs to transition Tanzanians to LNG-based cooking is unknown, since the LNG development is for export. It is our view that the gap between a future of widespread grassroots LNG-based cooking and the current solid fuel-based cooking is likely to persist for at least another decade, and that the introduction of sustainable biomass-based ICT is necessary to fill this gap.

Research location

Dodoma urban district is situated in the central (Dodoma) region of Tanzania and is the country capital. The region is semi-arid, with an annual rainfall averaging 570 mm. The biome was originally Miombo woodland savannah, characterized by *Acacia*, *Brachystegia*, and baobab trees. Most of the former two genera have been cut for firewood and charcoal, while the latter tree survives due mostly to its low wood value, difficulty to cut, and famine food value.

The regional population of nearly a half million is predominantly of the Gogo tribe, with a large minority of people from the many other tribal groups from all over Tanzania. The Gogo people have traditionally practiced a mix of pastoralism (cattle, goats, sheep) and crop production (maize and the indigenous millets and sorghum).

Cooking is done by the women of the extended family, in rural areas on a 3-stone fire in a cooking room/kitchen that is part of a long U-shaped mud-clay house that surrounds a courtyard. Ventilation is generally via a doorway. The nearly constant wind in this highland region (1,120 m elevation) generally necessitates cooking indoors. The urban district of Dodoma is made up of a higher proportion of non-Gogo people, and houses are generally of a design inherited from colonial times – rectangular and made of clay-cement brick. The cooking area is at the back of the house where the portable stove can be situated either indoors or out, depending on weather conditions. Charcoal is the predominant fuel and can be cooked with more readily outdoors in windy conditions than can the 3-stone fire or TLUD stove.

In order to gain a picture of the potential for the implementation of ICT and renewable biomass cooking in the Dodoma urban and peri-urban area we designed a basic set of stove and fuel test criteria that were consistent with our research resources and capabilities. We developed a cooking test that simulates typical household cooking conditions and compares the common fuels, charcoal and LNG, with biomass pellets; and compares the performance of three TLUD stoves with each other and with charcoal and gas stoves. The objectives were to 1) compare the cost of cooking with different fuels, and 2) compare the performance of a selection of ICTs, traditional charcoal stoves, and an LNG stove. We also carried out interviews of TLUD stove users to find out their views of the new technology.

MATERIALS AND METHODS

Cooking test

The cooking test was done using a common food, dry beans *(Phaseolus vulgaris)*. Beans were selected as a cooking test over standard water boiling tests, as we desired to test the cooking performance of stoves, not only the time to boil. Sustained boiling can occur at a low boil or at a vigorous boil, giving different times to cook a food like beans. The very limited laboratory resources at our disposal simply did not allow the precise measurement of such things as combustion efficiency and particulate emissions.

In a covered aluminum pot, 5 L water of temperature 22°C was brought to a boil and 250 ml dry red beans was added. The same type of beans was used for each test. Beans were considered cooked when they were easily mashed with a fork. Time to boil and time to cook was recorded. This was done 5-6 times for each stove. Following cooking the amount of soot on the bottom of the pot was recorded on a scale of 1-10; with 1 clean and 10 completely soot covered that included tar. All stoves were managed as the average African household would manage them, therefore performance results may differ substantially from results from stove developers and laboratories.

Fuel

Biomass for pellet fuel consisted of fallen leaves and stems of Eucalyptus tree species, rice hulls from the local rice mill, prunings from the many shrubs and trees on the university campus, waste from the harvest and threshing of sunflower, and maize cobs. The latter two are seasonal, from May to August. Biomass was first pulverized a hammer mill (Yulong SG40 hammer mill, Yulong Machine Co, Zhangqiu,China) with 3mm diameter sieve holes, resulting in shredded biomass of 1-3 mm diameter particles. Shredded biomass was blended to approximately one third each of Eucalyptus, rice hulls, and post-harvest sunflower field waste (stalks, inflorescences, leaves) and fed into the pellet mill (Yulong SJK-200 flat die, 6mm die diameter) along with approximately 250 ml water per 20L bucket of biomass. We found it best to add water simultaneously with the biomass. Extruded pellets were sun dried and stored in bags. Occasional plugging of the die holes, especially with new die plates, was a problem. These had to be individually drilled out. Higher oil content of the biomass stock helps to lubricate but also can result in a more smoky fuel. The same batch of pellets was used for each test.

The price for pellets was set by assessing the cost of production and sourcing of biomass. Our price of \$0.21 kg^{-1} is also a convenient 350 TZ shillings (TZs) per kg or 3 kg for TZs 1,000 (\$0.63). We found that this price was independently very close to other pellet projects in Tanzania and close to that of Inyenyeri in Rwanda.

Charcoal was locally sourced from charcoal vendors and was made from common tree species from Miombo woodland such as *Brachystegia* and *Acacia*, as well as numerous shrub species. LNG was obtained in portable tanks from Mihan Gas Inc., Dar es Salaam.

Stoves

Jiko Bomba Stove (Figure 2) (Bjarne Laustsen, Karatu, Tanzania, www.kiwlau.com, \$15). According to Roth (2014) The Jiko Bomba is “double-walled, locally produced TLUD-ND [natural draft] made of mild steel, optimised for pellets composed of mixtures of agricultural residues as a fuel. Diameter is 23 cm, height 37 cm. The stove is composed of two vertically stacked assemblies: the bottom part is the stove unit comprising a fuel reactor and a primary air regulator. The top part comprises a mixing chamber, an internal chimney space and pot-rests. Its perforated bottom plate enhances pre-mixing of wood-gas and oxygen before ignition in order to achieve clean combustion. Both assemblies have handles and pot-rests.” Metal thickness is approximately 20 gauge (0.9 mm).

Troika Stove (Figure 2) (Awamu Biomass Energy Ltd., Kampala, Uganda. Designed by Dr. Paul Anderson, www.drtlud.com, \$16). From Roth (2014): “The Troika model is the 2013 addition to the ‘Champion Family’ of TLUD cooking stoves that include Champion (2009), Mwoto (2010), and Quad (2012). All four stoves have the same basic dimensions and performance, but with distinct constructions. The Troika can be either ND (Natural Draft) or FA (Forced Air). The portable Awamu Troika TLUD is based on pre-cut parts with tabs and slots for easy local assembly without rivets and cheaper shipping as flat pack pieces. It has a metallic body with four wooden handles that allow for safe handling and also serve as legs to provide stability. Flatpacked parts weigh 4 kg; dimensions of assembled stove: 30 x 30 x 50 cm. The Troika can be made as a TChar variation to continue cooking with char.” Metal thickness: 24 gauge (0.6 mm).

St. John’s Stove (SJUT) (Figure 3). The St. John’s Stove was constructed by our project and consists of two concentric cylinders with perforations in the bottom plate for primary air as well as perforations at the lower end of the inner wall. The SJUT stove has no primary air vent. The SJUT2 has additional air vents at the top of the outer cylinder. The pot stand is inserted on top when initial lighting is complete and channels secondary air to the gases rising from the pellets.

Philips Fan Stove HD4012 (Figure 4) (African Clean Energy, Maseru, Lesotho. www.africancleanenergy.com, \$72. From The description in Roth (2014): The Philips stove is: “a high efficiency TLUD gasifier stove with forced air, stainless-steel construction; the inner combustion chamber is ceramic. The stove is virtually smokeless due to a good air-gas mixture for complete combustion that is created by the fan at the bottom of the combustion chamber. The battery can be charged either from the grid, if available, or using a solar charger.” A knob allows the fan to be adjusted from 4 to 12 V. The fan provides both primary and secondary air flow to the fuel. The Philips stove is designed primarily for the use of pellets but can also burn found fuels and small pieces of wood. The battery is said to drive the fan for 40-60 h, or 2-3 h per day for three weeks.

Traditional charcoal stove (Figure 5). This is generally an open bowl design of approximately 30 cm diameter with metal casing and 1-2 cm clay liner; the bottom is perforated with 1 cm holes. A closable air vent allows a small measure of turn-down. Improved charcoal stove (Figure 5) Envirofit CH2300 (www. arti-africa.org, \$33): Is an insulated open bowl (15x31x23 cm HxWxD) charcoal stove with adjustable air inlet.

Gas stove with a LNG/LPG gas burner (Hangzhou Tianlong Steel Cylinder Co., Zhejiang China) was used. The steel/chromium frame fastens directly to LNG tank.

Table 1. Summary of factors in choice of cooking system in Dodoma Tanzania 2013-14. Cost of cooking was done using consolidated data from Tables 2 and 3.

1 Fuel type	2 Weight of fuel to cook beans (kg)	3 Fuel cost US$/kg	4 Estimated cost to cook beans (US$)	5 Cooking system (stove) cost	6 Soot on pot	7 Smoke	8 Time from lighting to begin cooking (min)	9 Time to boil 5 L water
Natural Draft (ND) Pellet[1]	1.4	$0.21	$0.29	$20	High	High	3	33
Forced Air (FA) Pellet[2]	1.1	$0.21	$0.22	$75	Very low	Low	1	18
Charcoal[3]	0.6	$0.26	$0.15	$4	Med	Med	30	55
Liquefied natural gas (LNG)	0.28 – 0.47	$2.06	$0.64-$1.01	$70[5]	None	None	0	19-51[6]

[1] Average of Troika, Jiko Bomba, SJUT2. Does not include SJUT1 due to performance problems of that stove, [2] Philips stove, [3] Average of traditional and improved charcoal stoves
[4] Average of six tests at two different flow rates as described in Materials and Methods, [5] Cost includes 15 kg capacity gas tank (US$40) and basic 2-burner counter-top stove (US$30.

Cooking procedures

Solid fuels

Pellets were placed in the fuel chamber and ignited with approximately 30 ml of kerosene. The initial amount of pellets was 1 kg except the Philips, whose capacity was 600 g. The primary air vent in the Jiko Bomba and Troika stoves was open fully, and when the flame was strong the top part of the stoves was put in place and the primary air vent closed in increments. The St. John's stove lacks a primary air vent. The stove top serves to channel secondary air to the upward-moving gases in the ND stoves, as well serving to support the pot. When the flame gave the appearance of burning mostly gas cleanly (gas plus secondary air), the primary air in the Jiko Bomba and Troika was adjusted to approximately ¼ open and the pot with water was then placed on the stove. For the Philips, stove ignition was without fan for the first 30 s followed by medium fan power to get the flame going, and finally high power for the remainder of the cooking. The charcoal stoves had an initial ignition period of about 30 min before pot placement; this is one of the main disadvantages of charcoal.

All of the solid fuel stoves needed to be refilled when the fuel was depleted and reignited to finish bean cooking beans. When pellets were burned down to char (no flame, only glowing coals) the char was emptied and extinguished with sand and the fuel chamber refilled and reignited and time recording resumed. When the beans were fully cooked, this second batch of partially burned fuel was emptied, the char separated from unburned pellets, and the total weight of fuel used calculated by subtracting the unburned fuel from the total loaded. The char was weighed and quantified as a percent of total fuel used. With the charcoal the coals were extinguished with sand and weighed to assess total fuel used.

Gas

Weighing the amount of gas to cook each pot of beans was not possible; therefore we did the following in order to account for the fact that most people cook beans initially at high gas flame, then turn it down to different simmering rates:

A full tank of LNG was lit, set to medium-high flame, and the time recording started. Three lots of beans were cooked at medium-high flame and the time for each was recorded. The time to totally deplete the tank of gas, the entire time at the same medium-high flame, was recorded and the weight of gas used per minute calculated. The weight of gas per lot of beans was calculated as weight of gas used per minute times the time to cook the beans (gm gas min^{-1} x min).

A second full tank was lit, set to low flame, time recording started, and three batches of beans cooked at constant low (simmer) flame. The same method was used to calculate the time to cook the beans at low flame.

Stove introduction and interviews

The Jiko Bomba stove was promoted and sold at a subsidized trial price to the local community, as this stove was the only one available in sufficient quantity. Careful instructions on using the stove, particularly the air vent, were given. The first 30 purchasers of the Jiko Bomba stove were interviewed for their experience with the stoves. Interviews were conducted in Swahili language, the language of the respondents, by a Tanzanian post-Master's degree worker with experience in conducting interviews. The same questionnaire was used for all of the respondents.

RESULTS AND DISCUSSION

Evidence for the continued preference for charcoal-based cooking in Tanzania can be seen in Table 1. With charcoal, both cooking cost and stove cost are substantially lower than natural draft and forced air pellet systems and LNG, while pot soot (a proxy for smoke) is moderate. For the Philips fan stove and natural draft stoves respectively 83 and 133% more pellets by weight (column 2) were needed to cook beans than charcoal, costing 47 and 93% more than charcoal at 2013 charcoal prices. This cost difference will make it difficult to introduce pellet stoves. For successful adoption of such new technologies, the cost advantage must be substantial.

While this cost advantage for charcoal has devastating effects on the environment due to the continued drastically unsustainable cutting of trees, householders are likely to continue to ignore new types of ICT until the fuel cost is substantially lower than charcoal and the stove cost is not too high. However, given the steady price increase of charcoal, the transition to a situation in which cooking with charcoal costs substantially more than with pellets is inevitable. In Dodoma, charcoal prices are more than doubled from 2011 to 2014. According to the World Bank (Peter and Sander 2009), the price in Dar es Salaam for a 40-50 kg bag of charcoal rose from $3.50 to $13.30 between 2003 and 2007. Currently (end of 2014) that price is around $40. Another report (Energy and Environment Partnership 2013) shows charcoal prices increasing from US$0.09 to US$0.82 per kg from 2003-2012, an average annual increase of 99%. These figures indicate a 33%-90% annual increase in price, with the higher end being in the main city, Dar es Salaam. For this reason we continue to work on pellet-fueled systems despite current low rates of sustained adoption.

Smoke and soot from the natural draft stoves were a problem (Table 1). A thick layer of shiny tar-laden soot often coated the bottom of the pot after cooking. In laboratories and workshops microgasification stove developers are able to operate many of these stoves (i.e. Troika, Quad) with minimal smoke and soot, commonly attaining ISO Tier 3 (very little smoke) in the PM 2.5 (smoke) emission category and even attaining the much sought after and difficult to attain completely clean Tier 4 (Anderson, 2014). However, transferring the ability to attain even Tier 3 performance to African householders is going to be a challenge. Householders use different types of fuels and pellets made from different biomass stocks whose components frequently fall outside the parameter range that the stove is tuned for. Stove owners often hand off the stove to a maid with minimal instructions and walk away. The stove program workers who carried out the tests on the TLUD stoves for this research tended to have more knowledge than the average householder about using the stoves properly, that is, the primary air vent; but they were unable to use the natural draft stoves on biomass pellets without creating excessive smoke.

The Philips fan stove was clearly superior to the natural draft stoves in the smoke and soot category, as well as in time to boil, over 50% faster than the natural draft stoves (Table 1). While only one was available to use, the Philips stove having not been introduced to Tanzania, users who tried it were unanimous that it is superior. The 375% higher price for the Philips stove (Table 1) is a barrier however, as well as the requirement to charge the fan battery, needed for every two to three weeks of normal cooking. Since many Tanzanians who lack electricity in their homes are accustomed to charging devices like cell phones in neighbouring small shops, households that desire to incorporate the Philips stove into their cooking can use this method. A detachable battery would be useful in this case. The Philips stove ability to turn-down to a satisfactorily low simmer was a minor problem. According to the manufacturer this problem has been corrected with a new rheostat mechanism. Additionally, the stove producer, African Clean Energy, sells a solar panel charger for $17 (5W PET frameless panel with regulated 7V output to charge the 6V battery).

The 325 to 570% higher cost of cooking with LNG (depending on gas flow rate) (Table 1) compared to charcoal plus the high cost of gas stoves will be barriers to the great majority of Tanzanians to move to this ICT. Use of LNG for cooking will likely remain in the upper echelons of society until gas prices decrease and/or programs to subsidize equipment purchase are implemented. Targeting these LNG-cooking price barriers and the implementation of clean cooking should be a government priority given the astronomical costs to Tanzanian society of respiratory-related ill-health due to indoor air pollution from cooking smoke as well as deforestation for charcoal production.

The potential for reducing the cost of solid fuel cooking via subsidies from carbon credits (Global Alliance for Clean Cookstoves, undated) may make TLUD stoves and agricultural waste based fuels more competitive with other systems, particularly in combination with price increases of charcoal. Biochar produced by TLUD stove users and used as soil amendment may in the future be an additional source of carbon credit funds via carbon sequestration in soil (Figure 6) (Whitman et al., 2010; Interreg IVB project Biochar, 2013).

Biochar production of just under 60% of total fuel weight for the natural draft stoves (Table 2) is comparable to the percentage in at least one other study using microgasification stoves in East Africa (Whitman et al., 2011). The Philips forced air stove production of one third (29.8%) of that of the natural draft stoves reflects the more efficient use of fan-driven primary air reducing pyrolysis. This stove was not developed to produce biochar.

Of the 30 people interviewed who bought the Jiko Bomba TLUD stove, 18 (60%) were not using the stove after one month, stating that they were dissatisfied with the stove performance and had returned to using charcoal. Another three had stopped because pellets were difficult to obtain, only being available at the SJUT Stove Project site, which for some is a distance. Over 80% (25 of 30 respondents), said that the stoves produce too much smoke and blacken pots. However, 75% said that the pellet stoves heat better and cook faster than their charcoal stoves, as is evident in Table 2 cook times. Forty percent of users mentioned that controlling the air vent, which is the most important factor for controlling smoke, is too much trouble, and that with charcoal they can put the pot on and leave it for an hour. It was clear from the interviews that most of the stove users

Table 2. Performance comparison of two types of charcoal stove with two types of waste biomass pellet fuelled microgasification stove, forced air (FA) and natural draft (ND). Means and 95% confidence intervals are provided.

1	2	3	4	5	6	7	8
Stove	**Fuel type**	**Stove type**	**N**	**Biochar Percent**	**Weight fuel used (g)**	**Time to boil (min)**	**Time to cook beans[2] (min)**
Phillips	Pellet	FA	6	29.8a (18.9-40.7)	1088bd (918-1258)	18.5a (15.9-21.0)	105a (87-123)
Troika	Pellet	ND	6	50.8ab (37.8-63.9)	1494c (1294-1694)	26.3b (19.3-33.3)	102.5ab (89-115)
JikoBomba	Pellet	ND	6	56.8b (49.4-64.2)	1653c (1363-1943)	42.5c (34.0-51.0)	134ab (121-148)
SJUT1[1]	Pellet	ND	6	61.5ab (48.9-74.0)	728ab (453-1002)	64.2c (37.4-90.9)	165ab (135-195)
SJUT2	Pellet	ND	6	51.8ab (37.1-66.6)	1302cd (1079-1525)	63.8c (51.5-76.2)	180b (156-205)
CharTrad	Charcoal	Trad.	5	-	621a (503-739)	54.2c (30.2-78.2)	150ab (138 -163)
CharImpr	Charcoal	Improved	4	-	514a (320-514)	55.0c (29.8-80.2)	155ab (112-197)

[1] The SJUT1 stoves were experimental and the SJUT1 stove gave problems staying lit. We have decided to include it in the data. [2] Includes time to boil.

Figure 6. Typical soot with tar on pot bottom after cooking on natural draft TLUD stove with pellets.

had not learned the importance of adjusting the air vent, despite careful instructions at initial disbursement and a follow-up visit. This appears to be a major reason for the excessive smoke problem. The oil content of the pellets may play a role in smoke production; however, when the same pellets that produced smoke in the ND stoves were used in the Philips fan stove, smoke was not a problem. The 30 min ignition time for charcoal reduces its advantages, along with the longer cooking times.

The St. John's stoves (SJUT 1 and 2), while being the least expensive to produce due to their lack of a vent door, extinguished regularly after about 30 min, probably due to lack of a primary air intake vent. Fuel efficiency is high in the SJUT1 stove (Table 2, column 6) due to a different air configuration, but this does not overcome the problem of lack of sustained combustion. There might be potential for this stove to be used for short cooking times such as making tea and cooking corn meal (*ugali*) the most commonly cooked foods in Tanzania, which takes about 25 min.

The cost of biomass densification into pellets will need to decrease substantially relative to charcoal to become competitive. The small-scale imported machinery that we used gave problems with the die holes plugging up with the friction-heated biomass mix, slowing production and increasing its cost, as each of the approximately 100 die holes need to be drilled out. This has been a problem with other pellet-making groups in Tanzania. Wear and tear on the machinery necessitated the expensive replacement of imported parts such as the die and rollers, as well as the 3-phase electric motor. These problems increased the cost of production beyond the price to compete with charcoal in 2014. We chose to test these lower-end technologies because these are what local entrepreneurs generally buy. To be economically viable, biomass-based pellet production will likely need to be developed on a larger scale with higher quality machinery that is more resistant to wear and tear and that has a production volume high enough to support a maintenance and parts replacement program. Therefore the concept of local pellet-making using locally sourced biomass may not be viable based on our experience. Likely to be more viable will be large-scale plants that can supply the urban population of an entire region, located near production and processing operations that generate large amounts of waste biomass such as lumber mills and rice mills. The need to engineer a blend of different biomass stocks that meets the needs of pellet-making, such as blending eucalyptus prunings with rice hulls or sawdust, can be fulfilled by transporting the needed biomass. Hammer mills for reducing the volume of the transported biomass can be located at the local level since hammer mills generally give far fewer problems

Table 3. Cost of cooking with gas at low and high gas flow rates.

Gas flow rate	Total weight gas in tank (kg)	Total gas cost[1]	Gas cost US$/kg	Total time to use all gas in tank	Flow rate g/min	Time to boil 5 L (min)	Average bean cook time[2] (min)	Total gas to cook beans (kg)[3]	Cost US$ / hour	Aveerage cost to cook beans
Med-high flame	6.0	$12.94	$2.16	1231	4.87	19	96.5	0.47	$0.63	$1.01
Low flame	3.0	$6.76	$2.25	1479	2.03	51	140	0.283	$0.27	$0.64

[1] Doesn't include tank. [2] Includes time to boil. Three tests done for each flow rate. [3] Flow rate (g/min) times cook time (min).

than pelletizing machinery. An additional consideration is the cost of the microgasification stove. It appears that forced-air (FA) stoves will be the most viable option in the future; however these will likely be 5-10 times more expensive than natural draft (ND) stoves. While ND stoves are able to test nearly particulate free in laboratories, as discussed above, the everyday reality of keeping a ND stove tuned and vented properly may make the ND stoves non-viable for African households. FA stoves are more robust, the forced air causing consistently complete combustion of particulates with the simple turning of a rheostat. Such issues as damp pellets during the wet season are simply overridden by the combustion-facilitating power of forced air. Programs that subsidize or provide credit for the purchase of FA stoves would likely facilitate the transition to these ICTs once pellet fuels become available (Table 3).

Conclusion

Widespread adoption of solid fuel ICTs by the lower income 70% of urban and peri-urban African society will continue to be in a challenge if available ICTs do not substantially cut the cost of cooking while maintaining or improving customary cooking characteristics. Our results showed that the microgasification stoves used on the average twice the weight of pellets compared to charcoal (83% and 133% more by natural draft and forced air stoves, respectively). Therefore, until the price of pellets reaches somewhat less than half the cost of charcoal, there will be resistance to the adoption of the new stoves. However, relentless tree-based charcoal price increases will inevitably drive change, particularly as ICTs improve. The optimum configuration of ICT systems for Africa is still in need of shaking out and will likely involve numerous trials and failures.

Although most of the stove testers said that the pellet stoves cooked food faster than using charcoal, over half ended up abandoning the use of the microgasification stoves because they emitted too much smoke or were too much trouble to adjust for low smoke. When biochar is eventually given cash value by the agriculture market, microgasification stoves will be a significant source of this important soil fertility enhancer, as over half of the weight of burned pellets was turned into biochar. This may be significant in driving adoption of the new stoves.

Unless large-scale subsidization programs are developed for transitioning to gas cooking, the several-fold (387 - 570%) higher cost of cooking with gas will lock most of Tanzania’s population into cooking with biomass for some years to come, despite the exploitation of massive natural gas reserves in the country. African governments would do well to assess the needs of the many entrepreneurial efforts to introduce ICTs and to help pave the way for them. Education campaigns, tax breaks, tariff reductions for ICT technologies as well as strict enforcement of existing tree-cutting and charcoal selling laws can all facilitate the transition to ICTs. Justification of lax enforcement of such laws stems from the desperation of rural populations whose crops frequently fail due to drought, and must fall back on charcoal production. The paradox is that deforestation is associated with a worsening of drought conditions. Additionally, promotional and education campaigns to reduce household smoke pollution via better ventilation should assist with this.

It will be interesting to see how the cooking milieu and introduction of ICTs shakes out in the next 5 -10 years. Under trial in Eastern Africa are large-scale entrepreneurial pellet fuel production systems such as Inyenyeri in Rwanda, as well as smaller scale pellet and briquette making efforts. The production of “green charcoal” (Global Alliance for Clean Cookstoves, 2014) is being initiated in East Africa. Additionally, one must not underestimate the Chinese, who have developed clean biomass-based solid fuel cooking systems, particularly advanced pellet stoves, over the past 25 years and have the capacity to come into Africa on a large scale with low-cost and well developed solid fuel production and cooking systems.

Conflict of interest

The authors declared that there was no conflict of interest.

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