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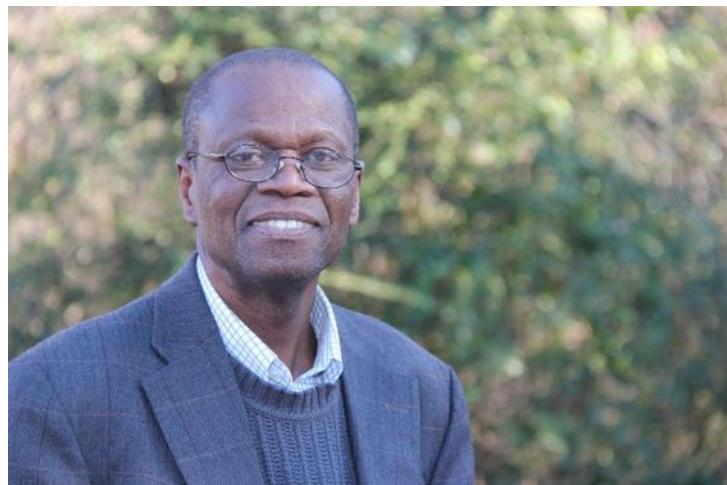
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ASSESSING ENERGY SOURCES FOR POWERING “EVAKUULA”

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ABSTRACT

Technologies that are appropriate, affordable, and sustainable are needed to increase incomes and resilience among sub-Saharan African smallholder farmers. A combination of thermization and low-cost evaporative cooling, termed Evakuuling, was developed to enable rural smallholder dairy farmers to preserve their evening milk in the absence of grid-electricity. The “EvaKuula” was configured to be powered by biogas. Biogas is used for the thermization process of the system. The evaporative cooling component is powered by wind. Use of biogas from domestic biogas plants add circularity value to smallholder farms. However, domestic biogas plant set-ups are relatively high capital investments and as such, a financial barrier to co-adoption with the *EvaKuula*. To lower this barrier, other energy sources have been considered. The purpose of this study was to assess alternative energy sources to power the thermization component of the *EvaKuula*. The list of energy sources considered included biogas, butane, kerosene, charcoal, and firewood. These energy sources were assessed with respect to the sum of the social and market costs. The product of a unit of fuel cost and the units consumed represented the “market cost.” The product of the long-term social carbon cost and total carbon dioxide emission equivalence represented the “social cost.” Regular and improved stoves were included in the charcoal and firewood analysis. As expected, biogas ranked on top of the list, followed by butane and kerosene. However, butane and kerosene are not easily accessible in rural setting. Approximated 76% of farmers in rural sub-Saharan Africa rely on firewood to meet domestic needs like cooking. Butane and kerosene are the fuel sources predominantly used in urban and peri-urban areas, due to accessibility and affordability. Incomes are typically higher among urban dwellers. Therefore, with butane and kerosene not readily available to the target *EvaKuula* users, the next best option was firewood, provided it is combusted in improved efficient stoves such as Lorena type.

Key words: alternative energy, evaporative cooling, sustainable development, food security, circularity, smallholder farmers



INTRODUCTION

A device to preserve the freshness of milk off-grid was developed for rural sub-Saharan African farmers. This device branded as “*EvaKuula*” has been deployed in Uganda in a pilot study. The components of the device are the thermization unit for the sanitization of raw milk with low heat (subpasteurization heat treatment) and the evaporative cooler for cooling to approximately 19°C [1]. The thermization unit process involves use of boiled water to indirectly heat-treat the milk to 63°C. The thermization water can in principle be boiled using any accessible fuel. The range of accessible fuels in Uganda include firewood, charcoal, kerosene, butane, and biogas. The choice of a fuel for household energy needs depends on several factors, such as accessibility and cost [2]. Smallholder farmers usually care about the cost and accessibility of a fuel but environmentalists in addition to the above also care about the environmental friendliness of a given fuel. Therefore, the recommendation of any fuel will need to be informed by both the priorities of the farmers and their stakeholders.

In Uganda, firewood is the most consumed fuel, estimated at 28 million tons of tree biomass and an additional 16 million tons of wood converted to charcoal [3]. The traditional three stone stoves with very low efficiency are mostly used resulting in fuel wastage because most heat is lost in open air [3]. This is mainly because farmers have limited cash flow [4] and can hardly afford the costs associated with advanced fuels or improved cooking devices. Charcoal is the most preferred form of energy for most urban households because charcoal has advantages over firewood that favor its use in the constrained space typical of urban settings. These advantages include: ease of storage, portability, smokeless burning, and simplicity of charcoal stoves [3]. *Albizia*, *Acacia*, *Grewia* spp, *Combretum*, *Allophylus* and *Terminalia* are the common tree species in Uganda’s woodlands that are utilized for charcoal production [5]. In addition to charcoal, some urban households use kerosene with specialized kerosene stoves for mainly cooking quick and/or light meals. Households in the middle-income status (earning more than five USD per day) and above, according to Banerjee and Duflo [6], tend to use energy sources such as a mix of butane and grid electricity, which are further up the energy cost ladder [2].

A decade ago, Uganda was estimated to have 600 biogas plants of capacities between 6 and 16 m³ installed across the country [7]. The most popular biogas plant size was 12 m³. But not all the 600 were operational. Uganda had a technical potential of more than 200,000 household biogas digesters and the potential was expected to increase as the zero-grazing movement and dairy industry expanded.

Based on the Pandey *et al.* [7] report, the Netherlands Development Organization (SNV) began to implement a program to develop and disseminate domestic biogas plants in rural and semi-urban areas in 2013. This has offered the Ugandan population the benefits derived from the use of biogas. These include: biogas for cooking and lighting and the bio-slurry (biogas plant effluent) as fertilizer for increased agricultural yields. The goal of the SNV program is to establish a sustainable and commercial biogas industry in Uganda. The SNV program is not the first program to attempt to develop a viable commercial biogas industry in Uganda. However, prior efforts from different development agencies have yielded little success as seen by the gap between the installed capacity (600 plants) and potential of the biogas plants (200,000 plants). A possible explanation is that the cost of cooking with woody biomass has been and is still perceived to be low in comparison to the investment needed for installing a biogas plant. Even when government policies are put in place to change behavior, lack of enforcement and/or corruption have more often than not defeated the purpose [8]. Additionally, cooking and lighting applications do not directly generate cash incomes, making it impossible for farmers to qualify for microcredit loans. The idea of cooling milk with biogas is likely to be a great opportunity, because the extra income generated by the evening milk is expected to make microcredit borrowing for biogas plant construction attainable. As such, adding milk cooling to cooking and lighting will make an investment into a biogas plant very attractive and, therefore, will quickly enable the narrowing of the gap between the installed capacity of 600 and potential of 200,000 plants.

The *EvaKuula* was designed with biogas as a fuel in mind because of its potential as a central component of the smallholder farm eco-system (Figure 1). However, as outlined above, a few smallholder farms or households have biogas plants. In the initial field deployment studies, it was found that the need to invest in a domestic biogas plant and *EvaKuula* at the same time was limiting the adoption of *EvaKuula*, due to the high capital cost needed for the biogas plant [1]. Therefore, the purpose of this study was to assess the accessible energy sources to recommend to *EvaKuula* potential adoptees to reduce the adoption implementation cost and as a first step, from which farmers can be encouraged to install domestic biogas plants after paying off the *EvaKuula*. In this study, kerosene, firewood, charcoal, and butane were evaluated in comparison to biogas, considering both the cost and environmental friendliness (greenhouse gas (GHG) emissions) of the fuel per liter of preserved milk. The findings and recommendations are presented herein.



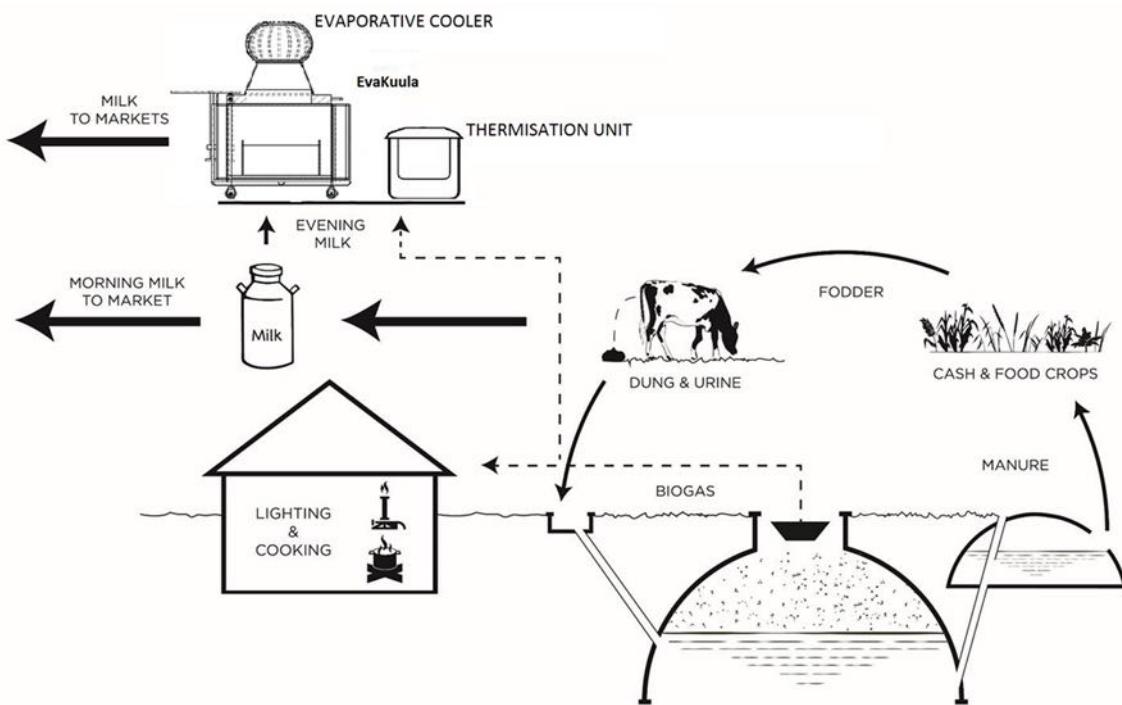


Figure 1: Renewable energy (biogas) powered milk cooler and the smallholder dairy farm ecosystem

From the cycle on the right (thin arrows), the cow feeds on the fodder, produces cow-dung that is fermented in the domestic plant to produce biogas. The slurry from the digester fertilizes crops/fodder that is consumed by the cow. From the digester, the biogas can be used for lighting and cooking, as well as milk cooling (dotted lines). While the morning milk (thick arrows) easily enters the market or cold chain, the evening milk cannot without the cooler, as it cannot be kept fresh until the next day, when the roads are passable and it is safer to travel. The use of biogas to cool the evening milk generates additional income, enabling investment in biogas technologies in low-resource settings, and creating a sustainable farm ecosystem in which the cooler, the biogas system, and the animals have symbiotic relationships.

METHODOLOGY

Energy quantity measurement

This research was conducted at the Smallholder Fortunes research facility located in Nsangi along Masaka road. The amount of fuel needed to bring a given thermization water volume to boil was determined. Boiling is a better marker as opposed to temperature, because water boils at different temperatures as different

elevations. Besides, in the hands of smallholder farmer users, it is much easier to know when the water is ready through observation of vigorous bubbling or boiling. The amount of water needed to thermize 10- and 20-liter milk loads have been previously determined through energy balance to be 14.18 and 26.26 liters, respectively [1]. This volume of water in a deep pan was heated to boiling with each of the fuels (Biogas, charcoal, wood, kerosene and LPG). The consumed fuel was measured as the difference between the initial and final weight/volume. The different stoves used in this study are presented in Figure 2 below.



A - regular charcoal stove,
 B - improved charcoal stove,
 C - three stone stove,
 D - improved firewood stove
 (Rocket Lorena stove type),
 E - kerosene stove,
 F - butane cylinder with burner,
 G - biogas digester floating
 dome type, with block on top to
 increase pressure under the
 dome, and H - biogas
 burner connected to the biogas
 digester.

Figure 2: Possible EvaKuula fuel/burner combinations evaluated

For the wood, and charcoal, the mass used to heat the water was determined by using Sj-20 KHS (SCALEPLUS, Allendale, MI) weighing scale. Charcoal and wood were weighed before heating water, and after the water boiled (separately), the remaining burning charcoal or wood was extinguished using water and sun-dried for at least 2 days and at most 4 days depending on weather. The moisture during drying was monitored until the desired levels (in the range 7-10%) were reached. The dried charcoal or wood was measured by using Sj-20 KHS weighing scale to determine how much fuel was consumed. Charcoal combustion was done using the traditional and improved stoves (Figure 2A and 2B). Wood was burnt using the three-stone stove (Figure 2C) and the improved stove, (Rocket Lorena type, Figure 2D). The improved stove was developed by the authors in partnership with Green Energy (www.greenbioenergy.org). The Rocket Lorena stove type was selected because previous studies reported its efficient use of firewood by reducing the amount of firewood used by 33%, in comparison with the three-stone fire arrangement [9]. The burning of charcoal and wood was done in open and well-ventilated spaces. The improved kerosene stove (cotton fiber wick type, Figure 2E) was used and fuel consumed was determined by measuring the kerosene volume before and after water boiling. Butane, alternatively called Liquefied Petroleum Gas (LPG), is sold in gas cylinders of mostly 6 and 12 kg weight. The 6 kg was used in this experiment. Butane consumption was determined by weighing the cylinder (Figure 2F) before and after boiling water. The floating dome type of biogas digester located at Smallholder Fortunes research facility was used to evaluate the biogas as an energy source. Figures 2G and 2H show the floating dome domestic biogas plant and the biogas burner, respectively, used for our studies. Bricks were placed on the floating component of the digester to provide pressure to drive the gas through the pipe network to the burner. The experiments were repeated at least three times for each energy source and the average fuel volume consumed was determined. The biogas consumed was calculated based on the change in the floating volume of the cylindrical floating dome before and after boiling water. The volume is computed by multiplying the surface area (diameter and height = 2.1m) of the floating cylinder and the change in height after boiling water. The burning of biogas, butane and kerosene was done in an enclosed but ventilated room.

Energy cost calculations

Current wood and charcoal costs were determined from a market survey in the town of Nsangi (on the Masaka highway, approximately 18 kilometers from Kampala), the closest trading center to Smallholder Fortunes Research/Demonstration Facility in month of July 2016. Kerosene and butane costs were surveyed from eight fuel stations situated in Nsangi, Kitemu, and



Kyengera towns along Masaka Highway, within 10 kilometers between Nsangi and Kampala. The biogas cost estimate was determined by depreciation of the capital cost of the digester over the approximate lifetime. The assumption was that there is no extra cost added to the digester over its lifetime. This is because for smallholder farmers who mainly use family labor on the farm (common of smallholder farmers in Uganda and sub-Saharan Africa as a whole), feeding of the digester usually comes with no extra financial cost. The marketing of biogas in balloon-like containers, in its initial stages in India, has not yet taken any roots in Uganda. Biogas packaged in this manner would provide more accurate price figures for this analysis.

A CAMARTEC biogas digester design was assumed for this study (https://www.researchgate.net/figure/Top-Typical-design-of-a-double-chamber-fixed-dome-biodigester-Model-CAMARTEC-Tanzania_fig1_334431738). This design has been heavily promoted in Uganda through an SNV (Netherland Development Agency)-backed biogas industry development program. The SNV has estimated the construction cost of this design to be \$604, \$788 and \$876 for the 6, 9 and 12 m³ capacities, respectively [10]. In tropical climates, fixed dome digesters like CAMARTECH produce 0.4 to 0.5 m³ biogas per day per 1m³ of digester volume [11]. Using an average production rate of 0.45 m³day⁻¹ m⁻³, the production of a 6 m³ digester comes to 2.7 m³ (6 x 0.45) day⁻¹. The lifetime of the digester has been approximated to be 20 years [10]. Therefore, the total production over the 20-year period would be 19,440 m³ (20 years x 12 months x 30 days x 2.7m³ day⁻¹). This comes to an estimated cost for biogas fuel of \$0.03 per m³ (\$604/19440m³) = \$0.03 kg⁻¹ (density =1.15kgm⁻³). The market cost was calculated as the product of the cost per kg of fuel and the consumption of the fuel in kg. For example, for biogas, the market cost comes to \$0.03 kg⁻¹ x consumed biogas in kg. A minimum of three cows is needed to maintain the 6 m³ digester.

Environmental impact determination

The total greenhouse gas emissions for each fuel studied was evaluated based on liters of milk preserved. The following gases were considered: CO₂, CH₄ and N₂O because they are the most prominent greenhouse gases emitted during stationary combustion [12]. According to the US Environment Protection Agency (EPA), CO₂ accounts for highest percentage, contributing about 76% of the global emissions. Therefore, CO₂ is the most concentrated gas in the atmosphere and can stay in the atmosphere for over 100 years. Gas emissions from firewood, butane, kerosene and biogas energy sources were calculated using equation 1 [13]. Emission factors for biogas are approximated to Landfill gas because they have similar composition. For charcoal, emissions were calculated using equation 2 because emission

factors for charcoal are expressed in units based on the mass of fuel burnt. The Environment Protection Agency (EPA) recommends Equation 1 for estimating emissions from stationary combustion because emission factors are based on energy units. However, in a circumstance where only consumption is known in mass or volume units, Equation 2 can be used [12]. Estimations using both equations do not differ significantly. The emission factors and high heating values used in equation 1 and 2 are presented in Table 1. Based on 100-year time horizon, the global warming potentials (GWP) relative to CO₂ are 21 for CH₄ and 310 for N₂O [14]. The emissions from equation 1 for each energy source were then converted to CO₂ equivalence using equation 3.

$$\text{Emissions} = \text{Fuel consumption} \times \text{High heating value} \times \text{EF}_1 \quad \dots \quad (1)$$

$$\text{Emissions} = \text{Fuel consumption} \times \text{EF}_2 \quad \dots \quad (2)$$

$$\text{CO}_2 \text{ equivalence} = \text{CO}_2 \text{ emission} + (21 \times \text{CH}_4 \text{ emissions}) + (310 \times \text{N}_2\text{O emissions}) \quad \dots \quad (3)$$

EF₁: Emission factors per energy unit of the fuel (kg of emissions/mmbtu) and EF₂: Emission factor per mass of fuel (kg of emissions per Kg of fuel).

The term “social carbon cost” was used to reflect the environmental impact of a fuel. The long-term social carbon cost for carbon dioxide emissions has been estimated as Euro 614ton⁻¹ of CO₂ [16], equivalent to USD 0.5/kg⁻¹ of CO₂ (Euro 1 = USD1.14). This social carbon cost estimate and the total equivalent CO₂ emission for each fuel are used to calculate the fuel social carbon cost. Therefore, the social cost of a fuel = \$0.5kg⁻¹ of CO₂ x (Carbon dioxide emission equivalence (kg)).

Determination of cost per liter of milk preserved

The term “aggregate cost” is used to represent the sum of the market and the environmental impact (social carbon cost) of a fuel. The consumption of fuel for both the 10 and 20 liters was evaluated since the scaling was not linear between the two capacities. The number of cows needed to produce 20 liters of milk depends on cow production rate. The cost per liter of milk preserved for each energy source was calculated as the aggregate cost divided by the quantity of milk thermized (for example, aggregate cost per 10 or 20). The aggregate cost and cost per liter for each energy source are presented as averages. Analysis of variance was used to test for significant differences in the cost per liter of milk between energy sources.

RESULTS AND DISCUSSION

Utilized energy cost

The results of the survey showed that butane cost was higher (USD 2.99/kg) in comparison with other fuels. Kerosene was next (USD 0.84/kg), followed by charcoal (USD 0.26/kg), firewood (USD 0.06/kg), and biogas, estimated at USD 0.03/kg.

Results for fuel consumption per liter of milk are presented in Table 2. The consumption of the fuel decreased in the order of firewood, charcoal, biogas, kerosene, and butane for both the 10- and 20-liter milk capacities. This decrease in the amount needed for each fuel can be attributed mainly to the difference in the fuel calorific values. For example, firewood has a gross calorific value between 14.4 and 17.4 MJ/kg when dry, and charcoal, kerosene, butane, and biogas have calorific values of 29.6, 46.2, 49.5 [17] and 19.1MJ/kg [18], respectively.

Market costs

The term “market cost” was used to represent the cost of fuel consumed during thermization. The market cost of each fuel used for both the 10- or 20-liter milk loads are presented in Table 3. Using biogas (originally intended energy source for powering the *EvaKuula*) as the datum, the market cost for butane, charcoal in a regular stove, kerosene, charcoal in an efficient stove, firewood in the three stone firewood stove, and firewood in the Rocket Lorena stove were 51, 27, 25, 17, 16, and 10-fold, respectively, for 10-liter milk load. However, for 20-liter milk load, the fold increases were 31, 14, 12, 9, 8, and 5 respectively. Therefore, the energy consumption trends were similar for both 10- and 20-liter milk loads as shown in Figure 3A. The high butane cost was not surprising as butane is considered up the energy cost ladder. It was also not surprising for the firewood in Rocket Lorena stove cost to be lower than that for firewood in the three stone stove. The Rocket Lorena stove yielded firewood savings of 21% and 30% for 10- and 20-liter milk loads, respectively. However, repeated Rocket Lorena stove use soon after the first use – when still warm – yielded firewood savings of 21.09% and 36.5% for 10- and 20-liter milk loads, respectively. The high firewood saving because of repeated use is likely to be highly characteristic for a typical farmer. Farmers will use the stove for normal household cooking, followed by water boiling for the milk thermization process. In this analysis, Rocket Lorena firewood costs were based on first use - from cold stove - to be consistent with other stoves that were started from the cold state.



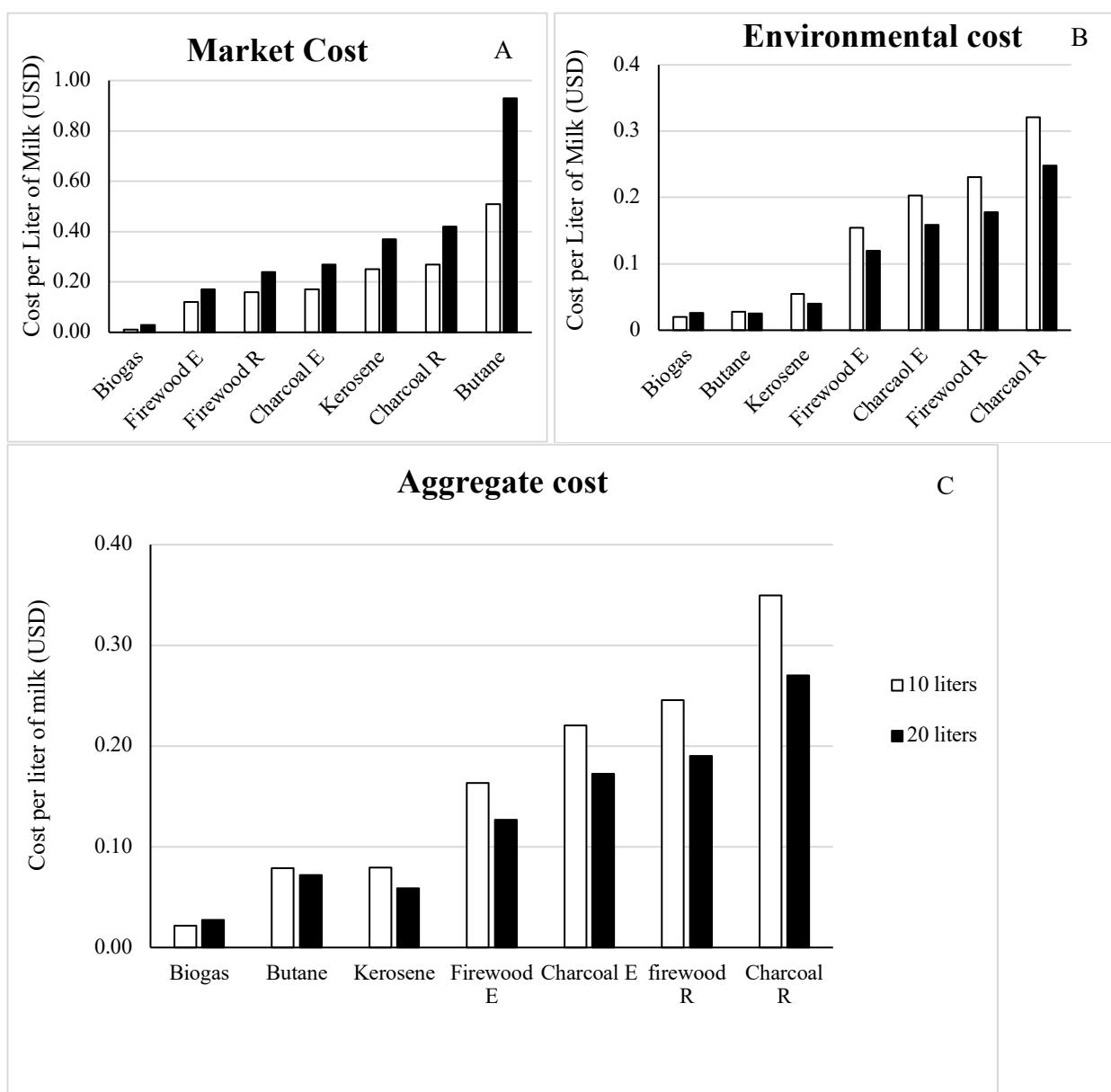


Figure 3: Bar graphs showing the Market, Environmental (social) and Aggregate cost per liter of milk for energy source

There was a similar trend in the market, social and aggregate cost per liter when thermizing both the 10 and 20 liters of milk. From graph A, Butane had the highest cost per liter. This is because butane as a fuel costs relatively high per kilogram on the local Ugandan market compared to other fuels. Based on the market cost, Firewood E (firewood in an efficient stove) offered the next alternative after biogas. From graph B, Firewood R (firewood in a regular 3-stone stove) presented the highest social cost per liter. This means that using a 3-stove for thermization would be the most environmentally damaging. Butane and kerosene presented the least environmental cost per liter after biogas. From graph C, the aggregated cost per

liter suggested that butane presented the next alternative to biogas whereas Charcoal R (Charcoal in the regular stove) presented the worst choice.

Social costs

Table 3 presents the GWPs of selected greenhouse gas emissions expressed in kilograms of carbon dioxide resulting from thermization for both the 10- and 20-liter milk load. Generally, the GWP in terms of kilograms of carbon dioxide was highest in charcoal and decreased in order of charcoal, firewood, kerosene, butane and biogas. Therefore, charcoal is considered a dirty fuel because of its high carbon content [19], which explains its higher GWP compared to other fuels. A higher GWP is associated with a higher social cost. Therefore, the results suggest that biogas is the cleanest fuel and thus, has the lowest social cost compared to the other fuels. The results compare with those reported in literature. For example, the energy ladder has ranked these fuels in a similar pattern [19]. With biogas as the datum, fold increases of the social cost for butane, kerosene, firewood in a Rocket Lorena stove, firewood in a three stone stove, charcoal in an efficient stove, and charcoal in a regular stove, were 1, 3, 8, 11, 10 and 16, respectively, for a 10-liter milk load. A similar fold increase trend was observed with 20-liter milk load of 1, 1, 5, 7, 6 and 10 in the same order, respectively. The higher the social cost associated with the energy source, the more “unfriendly” the use of the energy source is to the environment [20]. Therefore, for *EvaKuula* application, based on environmental friendliness, energy sources can be ranked as biogas, butane, kerosene, firewood in a Rocket stove, firewood in a three-stone stove, charcoal in an efficient stove and charcoal in a regular stove as shown in Figure 3B.

Aggregate costs

The aggregate cost (sum of social and market costs) per liter of cooled milk for both the 10- and 20-liter milk loads are shown in Table 3. With biogas as the datum, the aggregate cost for energy sources increased in folds of 17, 11, 12, 8, 4 and 4 for charcoal in a regular stove, charcoal in an efficient stove, firewood in a three-stone stove, firewood in a Rocket Lorena stove, kerosene, and butane, respectively for 10-liter of milk load. While for 20-liter milk loads, the fold increases were 9, 6, 6, 4, 2 and 2 in same order.

The analysis of variance (ANOVA) revealed a significant difference (p value < 0.001) in the cost per liter depending on the energy source used (Table 3). Post-hoc analysis suggested a significant difference (p value < 0.05) in cost per liter between charcoal use and other fuels, and between firewood and other fuels. However, biogas was not significantly different (p value > 0.05) from butane and kerosene. Charcoal and firewood fuels' use were significantly different between

regular charcoal and improved stoves that save about 36% of the fuel. As expected, using improved stove to power the *EvaKuula* results into savings for the household both environmentally and economically. However, an improved charcoal stove is not significantly different from firewood in three-stone stoves. For biogas, the cost per liter for the energy sources increased in folds of 17, 11, 12, 8, 4 and 4 for charcoal in a regular stove, charcoal in an efficient stove, firewood in a three-stone stove, firewood in a Rocket Lorena stove, kerosene and butane, respectively, for 10-Lmilk batches. While for 20-L load batches, the fold increases were 9, 6, 6, 4, 2 and 2, respectively. Energy sources can be ranked from the least aggregate cost per liter after biogas as; butane, kerosene, firewood in rocket stove, charcoal in an efficient stove, firewood in a three-stone stove and charcoal in a regular stove as shown in Figure 3C.

The variation in energy prices used in this study is consistent in other regions of Uganda. For example, in Northern Uganda, one can never find the cost of butane lower than the cost of charcoal or wood or kerosene. There may be slight differences in prices of these fuels in other regions of Uganda, but consistency is expected for unit cost with those reported in the peri-urban Areas of Nsangi near Kampala. The authors are confident that the results and conclusion in this paper will not change for other regions. Also, labor associated with each energy source was not included in this study because households using *EvaKuula* (smallholder dairy farmers) rely on family labor. Realistic estimation of labor in such contexts is not easy, but can be done, perhaps in a follow-up study.

CONCLUSION

In conclusion, these fuels are ranked using cost per liter beginning with the most preferred in the order of biogas, butane, kerosene, firewood, and charcoal. This suggests that the next alternative fuel to power the *EvaKuula* unit can be either kerosene or butane. Studies have approximated that 76% of rural sub-Saharan African farmers household rely on firewood to meet domestic needs like cooking. Butane and kerosene are the fuel sources predominantly used in urban and peri-urban areas, due to accessibility and affordability. Incomes are typically higher among urban dwellers. Therefore, with butane and kerosene not readily available to the target *EvaKuula* users, the next best option is firewood. However, powering the *EvaKuula* using firewood can only be economical and environmentally friendly when combusted in an efficient stove.

Conflict of Interest

The authors have no conflict of interest to declare.



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Table 1: Emission factors of greenhouse gases for each fuel

Fuel	Emission factors (kg of emissions/mmbtu)			High Heating value (mmbtu/kg of fuel)	Reference
	CO ₂	CH ₄	N ₂ O		
Butane	64.77	0.0003	0.00006	0.047	[11]
Biogas	52.07	0.0032	0.0006	0.016	[11]
firewood	93.8	0.0072	0.0036	0.017	[11]
Kerosene	75.2	0.0003	0.00006	0.045	[11]
Charcoal*	4.337	0.055	0.0004	-	[15]

* Emission factors (EF₂) expressed in kg of emissions per Kg of fuel

Table 2: Fuel consumption

Fuel	Ten-liter milk load (kg of fuel)	Twenty-liter milk load (kg of fuel)
Charcoal ¹ (kg)	1.06±0.13	1.64±0.05
Charcoal ² (kg)	0.67±0.05	1.05±0.25
Biogas (kg)	0.45±0.03	1.17±0.13
Kerosene (kg)	0.23±0.02	0.44±0.02
Firewood ³ (kg)	2.56±0.15	3.97±0.23
Firewood ⁴ (kg)	2.03±0.07	2.78±0.03
Butane (kg)	0.17±0.00	0.31±0.01

¹Regular inefficient stove; ²Efficient stove; ³Three-stone stove; ⁴Rochet Lorena stove

Table 3: Emissions, global warming potential (GWP), market cost, social cost, and aggregate

Fuel	Emissions (kg)			Total emissions (equivalent-Kg CO ₂)	Cost (USD)			
	CO ₂	CH ₄	N ₂ O		Market	Social	Aggregate	Per liter*
10-liter milk load								
Charcoal ¹	4.597	0.058	0.004	5.946	0.27	3.21	3.48	0.35 ^a
Charcoal ²	2.906	0.037	0.003	3.759	0.17	2.03	2.20	0.22 ^b
Biogas	0.367	0.000	0.000	0.369	0.01	0.20	0.21	0.02 ^e
Kerosene	1.005	0.000	0.000	1.008	0.25	0.54	0.79	0.08 ^d
Firewood ³	4.214	0.000	0.000	4.271	0.16	2.31	2.47	0.25 ^b
Firewood ⁴	2.820	0.000	0.000	2.858	0.12	1.54	1.66	0.17 ^c
Butane	0.517	0.000	0.000	0.519	0.51	0.28	0.79	0.08 ^d
20-liter milk load								
Charcoal ¹	7.113	0.090	0.006	9.200	0.42	4.97	5.39	0.27 ^f
Charcoal ²	4.554	0.058	0.004	5.890	0.27	3.18	3.45	0.17 ^{gh}
Biogas	0.954	0.000	0.000	0.958	0.03	0.52	0.55	0.03 ⁱ
Kerosene	1.474	0.000	0.000	1.479	0.37	0.80	1.17	0.06 ⁱ
Firewood ³	6.509	0.000	0.000	6.597	0.24	3.56	3.80	0.19 ^g
Firewood ⁴	4.361	0.000	0.000	4.420	0.17	2.39	2.56	0.13 ^h
Butane	0.942	0.000	0.000	0.946	0.93	0.51	1.44	0.07 ⁱ

¹Regular stove; ²Efficient stove; ³Three-stone stove; ⁴Rochet stove; *Values with the same letters are not significantly different from each other (P value < 0.05, n = 3 for each fuel). 1 USD = 3340 UGX

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