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Factors affecting fuelwood consumption in household cookstoves in an isolated rural West African village

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ABSTRACT

This study examines the factors that affect fuelwood consumption in cookstoves and estimates fuelwood consumption associated with the use of cookstoves in a rural isolated West African village with a population of 770. Five primary applications of cookstoves were identified: cooking meals, heating water for washing, roasting peanuts, making medicine, and steeping tea. Six factors were identified that significantly impacted cooking energy use: the type of cookstove application, family size, total mass of wet and dry ingredients, mass of dry ingredients, the use of burning embers as an igniter, and the number of fires used during a cooking event. Annual village fuelwood use for all cookstove applications was 234 metric tons; cooking meals and heating water accounted for 65% and 27% of this fuelwood use, respectively. Fuelwood consumption per person was strongly linked with family size. As family size increased from five to 20 members, fuelwood consumption decreased from 20.6 MJ cap^{-1} day^{-1} to 10.5 MJ cap^{-1} day^{-1}.

1. Introduction

Biomass cookstoves are common in households throughout the developing world and have significant health, safety, and environmental consequences [1–3]. As a result, there have been a number of efforts to provide improved cooking solutions for the communities in the developing world. Many of these efforts introduce new cooking technologies, for example solar [4], multi-function thermoelectric cookstoves [5], off-grid PV solar community kitchens [6] and biogas digestors [7]. Other efforts have also suggested focusing on shifting to low-emission liquid or gaseous fuel cookstoves [4,8]. However, many communities have existing distribution networks for wood and other solid biomass fuels and continue to use traditional biomass cookstoves [9,10]. Because of this, a number of laboratory and field studies have examined the performance of biomass cookstoves in the developing world. These studies have included detailed comparisons of cookstove performance in the laboratory that focus on efficiency, emissions, and safety [11,12]. Several studies have examined the health impact of cookstoves on households in the developing world [13–15]. Another set of studies have examined the factors impacting improved cookstove adoption [16–18].

Two common field studies that compare cookstoves are the controlled cooking test (CCT) and the kitchen performance test (KPT). The CCT is used to determine cookstove performance in cooking a standardized local meal prepared in a standardized way [19]. The KPT is used to compare cookstoves using in-home cooking tests in which the meals are selected and prepared by users [20]. Daily fuel consumption is compared between families that use different cookstoves or compared between two periods in which a single family uses a different cookstove in each period. Fuel consumption is measured once per day. Both the CCT and the KPT compare cookstoves by dividing wood consumption by an equalizing metric-meal mass in the case of the CCT and a standard adult equivalent in the case of the KPT. The standard adult equivalent adjusts family size using demographic information [21,22]. Other standardization methods have been proposed, as reviewed by Howes [23].

Several studies have reported factors other than cookstove type that affect energy use for cooking applications including heating water. Studies in India using simple linear regression found moderately strong correlations between meal size and cooking energy use ($R^2 = 0.77$) [24], and annual total cereal consumption and cooking fuelwood consumption ($R^2 = 0.77$) [25]. Another study found a poor correlation between the quantity of dry food cooked and cooking energy use per kg of dry food for cooking plantains in Uganda ($R^2 = 0.18–0.29$) and a good correlation for cooking beans in Tanzania ($R^2 = 0.69–0.81$) [26]. A study in Bangladesh reported

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that family size was positively correlated to daily fuel consumption (R^2 = 0.79) [27]. Another study in Bangladesh applied multiple regression analysis to examine the effect of population, annual income, and total land area on the total domestic wood use for small clusters of homes ($R^2 = 0.71$) [28]. Although each parameter was significant during single regression, only population was significant when including all three parameters in multiple regression analysis. In Kenya, multiple regression analysis applied to survey data from 572 households found that family size, dietary habits, and time spent to collect wood could be used to explain wood use for cooking and heating, but the weak correlation ($R^2 = 0.21$) suggests that factors not recorded during the study may be significant [29]. In comparing studies using simple regression with those using multiple regression, it is interesting to note that neither study using multiple regression included meal size in the analysis, whereas it was the only factor tested in all but one study using single regression.

This study examines seventeen factors that may affect energy consumption for cookstove uses in a rural isolated West African village. In contrast to studies that compare cookstoves, the goal of this study was to identify and understand the factors that affect fuel consumption for cooking, heating, and other cookstove applications. All methods and data discussed in this paper were approved by the Institutional Review Board at Iowa State University.

2. Study location

The village in this study lies within the Sahel of sub-Saharan Africa in Mali. The Sahel is a transition region between the Sahara desert and the forests of the mid-continent in Africa. Three seasons occur in the region: hot and dry (February–May); rainy and humid with moderate temperatures (June–October); and cool and dry (November–January). Approximately two-thirds of Mali's 13 million people live in rural areas [30]. These rural areas commonly lack basic infrastructure. Mali has the sixth highest rate of death in the world due to indoor and outdoor air and water pollution [31]. On a national level, biomass accounts for 78% of energy use [32], and over 99% of households use solid fuels for domestic energy needs [33]. The national per capita energy use of 7500 MJ cap^{-1} yr^{-1} is one-third of the average in Africa [32]. Per capita energy use in the study village is 6000 MJ cap^{-1} yr^{-1}, and the energy use associated with domestic cooking and other cookstove applications accounts for 75% of village energy use [9].

The village has 60 families with a total population of 770 people. All families live on subsistence agriculture, and during the rainy season approximately 10% of the residents live outside the village in small camps adjacent to their farmland. There is no access to the electrical grid, and travel is by foot and bicycle on dirt roads. A market 35 km from the village is accessible by a small bus that departs daily. Any goods not available in the village can be sourced from the market by bus; however, many of the goods used in the village are supplied by local artisans including blacksmiths, bakers, tailors, carpenters, furniture makers, brick makers, potters, and basket makers. Public buildings and services include a mosque, a bank with total deposits less than US$2000, a primary school for children, a clinic for primary care that is staffed part time by a nurse and a midwife, and a small pharmacy. Homes are commonly made from uncompressed earthen blocks and thatch roofs. Kitchens are made from wattle and daub and are separate structures from the main living space.

3. Methodology

Four visits to the village were completed. The first visit in May 2009 was used to plan the study, followed by three field studies of four weeks each to complete cooking studies in May, August, and December of 2010. These times were chosen because data from the planning visit suggested seasonal variations in energy use.

3.1. Initial planning study

The initial planning study identified factors that may influence cookstove use and fuel consumption. Data were gathered from interviews and participant observations. Due to cultural practices only women use cookstoves. The women responsible for cooking were interviewed to determine (a) the type and quantity of cookstoves owned, (b) the location of cooking and other cookstove applications, (c) the types of cookstove applications, (d) how often each cookstove application was completed, (e) how often each cookstove was used for each application, and (f) seasonal variations in cooking practices. Participant observations of women were completed for all cookstove applications. Based on an earlier survey of village population, the families in the village were stratified by family size: 2–6 (20%), 7–11 (27%), 12–16 (22%), 17–21 (13%), and 22 or more people (18%). Five families (one from each stratum) were chosen for participant observation. Families were not selected at random, but rather selected to ensure that all cookstoves and cookstove applications could be observed during the planning period. Income brackets were not considered during the selection process because the majority of household income is nonmonetary.

Findings from this initial planning visit are supplemented with data from the field studies for completeness. These findings include:

- Cookstoves: There are six types of cookstoves in the village, as shown in Fig. 1: (a) a traditional three-stone fire, (b) a traditional gakourouwana (GK) cookstove with one or more cooking hobs, (c) a low thermal capacity (LTC) cookstove made from clay and straw blocks, (d) a hand-crafted metal (HCM) cookstove made in Mali for cooking meals, (e) a manufactured metal (MM) cookstove distributed worldwide, and (f) a hand-crafted metal cookstove made in Mali for brewing tea. All cookstoves use wood, except for the tea cookstove, which uses charcoal. The low thermal capacity cookstove and the manufactured metal cookstove are improved cookstoves and were introduced by a non-governmental organization one to two years before this study at no cost to the user.
- Cookstove ownership: As shown in Table 1, the 123 women in the village using cookstoves can be categorized into 13 distinct sub-groups based on cookstove ownership. All women own a traditional three-stone fire or a traditional gakourouwana cookstove. The three-stone fire is owned by nearly all women (98.4%). Approximately one-half of the women own more than one cookstove (48.0%), 14.6% own both types of traditional cookstoves, and 43.9% own a traditional cookstove and an improved cookstove (low thermal capacity, hand-crafted metal, or manufactured metal). No women own only improved cookstoves. More than one-third of the women share cookstoves (38.2%). All families own at least one small charcoal stove for steeping tea.
- Cookstove use: The three-stone fire is used for nearly all cookstove applications (Table 2). Meal porridge and sauce are cooked on a traditional cookstove and an improved cookstove, respectively, if they are not prepared on the same cookstove. The low thermal capacity and manufactured metal cookstoves are used for smaller meals or sauces.
- Cookstove applications: Cookstove applications include six meal types and five non-meal cookstove applications (Table 2). Two meal types are commonly eaten for breakfast and four meal types are commonly eaten for lunch and dinner. Most

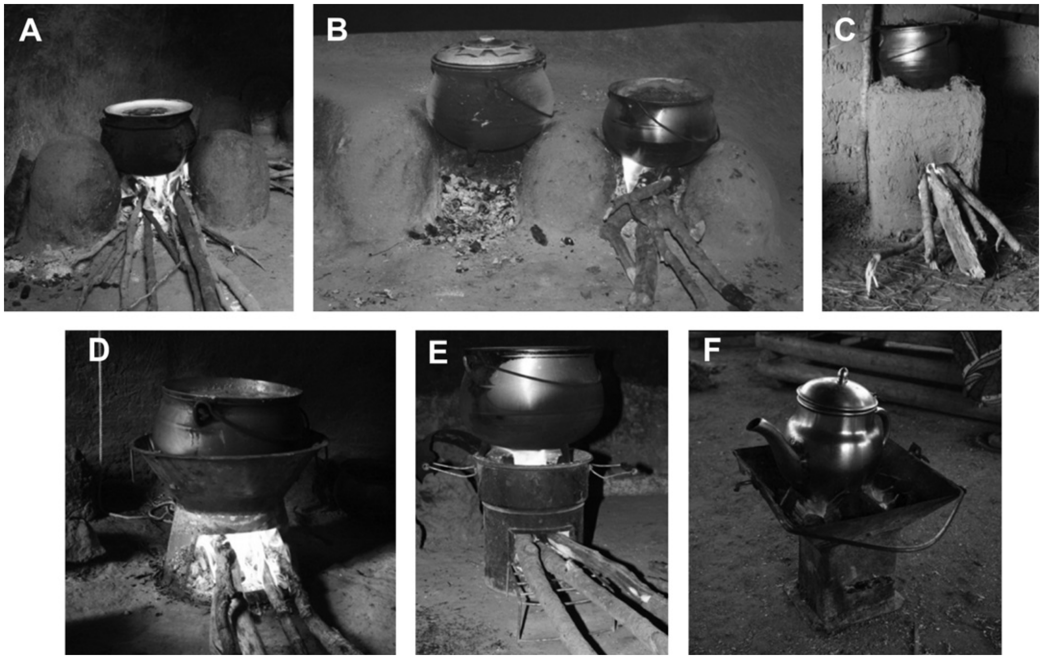

Fig. 1. Cookstoves: (A) three-stone fire, (B) gakourouwana, (C) low thermal capacity, (D) hand-crafted metal, (E) manufactured metal, and (F) charcoal tea.

meals include porridge. Modifications to these basic meals include changing the grain type (corn, millet, or rice) or changing the sauce type (leaves, peanut, or okra). Noting that cookstove applications include both cooking and non-cooking activities, the term "cooking" is used in this paper to refer to all traditional household applications of cookstoves except where this usage may result in confusion.

- Cooked mass: Meal size ranged from 1.3 to 24.7 kg meal^{-1} for the families observed. Per capita food consumption for lunch and dinner meals is 65% larger than the per capita food consumption for breakfast meals. Total daily food consumption for a family can differ by up to 44% between consecutive days. The cookstove application with the largest cooked mass was boiling shea kernels at 45 kg.
- Meal composition: The percentage of dry ingredients to the total meal mass before cooking ranged from 9.7% to 26.8% for breakfast porridge meals and 17.0–32.1% for lunch and dinner meals with porridge and sauce.
- Cooking vessels: The only type of cooking vessel in the village is an aluminum pot that ranges in capacity from 1 to 50 L.
- Fuel use: Cooking meals and heating water are the primary contributors to domestic cookstove fuelwood consumption.
- Fuel properties: Eight types of wood were commonly used as fuel. Wood varied in thickness from less than 1 cm to more than 10 cm in diameter.
- Number eating: The smallest family has two people and the largest family has more than 40 people. Each family eats meals from a separate cooking fire.

Table 1
Cookstove ownership in the village.

Number of cookstoves (% of total cooks)	Number of cooks	Cookstove ownership[a]				
		TSF	GK	LTC	HCM	MM
1 Cookstove (52.0%)	63	X				
	1		X			
2 Cookstoves (35.8%)	29	X		X		
	6	X			X	
	5	X	X			
	3	X				X
	1		X	X		
3 Cookstoves (8.1%)	5	X	X	X		
	3	X	X			X
	1	X		X	X	
	1	X		X		X
4 Cookstoves (2.4%)	3	X	X	X	X	
5 Cookstoves (1.6%)	2	X	X	X	X	X
Total cooks (% of total cooks)	123 (100%)	121 (98.4%)	20 (16.3%)	42 (34.1%)	12 (9.8%)	9 (7.3%)

Note: Percentages in first column do not add to 100% due to rounding. Percentages in the bottom row do not add to 100% because some women own multiple cookstoves.
[a] Three-stone fire (TSF), gakourouwana (GK), low thermal capacity (LTC), hand-crafted metal (HCM), manufactured metal (MM).

Table 2
Cookstove use in the village.

Cookstove applications		Cookstove use[a]				
		TSF	GK	LTC	HCM	MM
Meals	Breakfast porridge (thin)	X	X	X	X	X
	Breakfast porridge (thick)	X	X	X	X	X
	Meal porridge (thin) with sauce	X	X	X	X	
	Meal porridge (thick) with sauce	X	X	X	X	
	Couscous	X	X	X		
	Steamed rice	X	X	X	X	
	Meal porridge[b]	X	X	X	X	
	Sauce[b]	X		X	X	X
Other	Heating water	X	X	X	X	X
	Making medicine	X	X			
	Roasting peanuts	X				
	Boiling shea kernel	X				
	Rendering shea oil	X				
Maximum mass of ingredients in cooking vessel (kg)[c]		45	18	6	18	9

[a] Three-stone fire (TSF), gakourouwana (GK), low thermal capacity (LTC), hand-crafted metal (HCM), manufactured metal (MM) (tea charcoal not shown).
[b] Meal porridge and sauce cooked on different cookstove types.
[c] Observed from 84 cooking studies (discussed later).

- Family structure: The polygamous family structure in the village often includes several women per family who exchange cooking duties every few days. Commonly, women within the same family each have separate kitchens and cookstoves.
- Cooking location: The cooking location depends on the season and cooking activity. Cooking takes place outdoors or within an enclosed kitchen. Meals are commonly prepared in the enclosed kitchen, but are prepared outside during the hottest days of the year (40 °C and higher). Hot water is commonly prepared on an outdoor fire.
- Cooking practices: Women spend up to 20 min away from the fire to gather water, prepare ingredients, or tend to children. Women prefer stoking a large fire that will not smolder during this time. Each cookstove application uses one active fire, except meals with porridge and sauce, which may use two active fires.
- Ignition method: Methods used to start a fire include (a) a butane lighter with straw, (b) a butane lighter with plastic or trash, or (c) burning embers from another cooking fire.

3.2. Cooking studies

Cooking studies were completed during three four-week field visits. Findings from the planning study suggested that the following 17 factors may affect fuel consumption: (1) type of cookstove application, (2) type of ingredients, (3) mass of dry ingredients, (4) mass of water, (5) total initial mass of dry ingredients and water, (6) number of people benefiting from the cookstove application (e.g., number of people eating a meal), (7) standardized number of people based on age and gender, (8) cookstove type, (9) cookstove operator, (10) wood species, (11) wood moisture content, (12) wood size, (13) ignition method, (14) cooking vessel size, (15) season, (16) the number of cooking fires, and (17) the time of day. As a part of this study three tests were designed to provide contrasting data to examine the impact of these factors. The tests were strictly observational. No wood or food ingredients were provided and no instructions were given to respondents so that they would cook as if it were a typical day. The data listed in Table 3 are gathered for the following three test types:

- The Observational Cooking Test (OCT) gathers data from direct observation of the cook. The mass of fuel, the mass of all meal ingredients, and the mass of the cooking vessel are measured at the beginning of the cooking session. If burning embers are taken from another fire and used to start the test fire, the mass of the embers is also recorded. Demographic information and the number of people benefiting from the cookstove application are recorded. At the conclusion of cooking, the amount of fuel remaining, charcoal remaining, and the mass of cooked ingredients are weighed and recorded. A log of the cook's activities is recorded as time-series data (e.g., tending the fire, preparing meal ingredients, placing the pot lid on or off the cooking vessel, leaving the kitchen to collect water). No questions are asked during cooking sessions to avoid influencing test results.

Table 3
Overview of household cooking tests.

	Observational cooking test	Session cooking test	Daily cooking test
Test description	Researcher observes the cooking session to record a time-series log of operator tasks	Researcher measures data at the start and end of each cooking session but does not observe cooking	Researcher measures data once per day for cooking sessions completed that day
Quantitative data	Mass wood initial Mass wood final Mass of igniter Mass ending charcoal Mass of each ingredient Mass of cooked food Mass cooking vessels Number of people eating Demographic information Time-series cooking activity log	Mass wood initial Mass wood final Mass of each ingredient Number of people eating Demographic information	Mass wood initial Mass wood final Number of people eating Demographic information
Categorical data	Cookstove application Cooking ingredients Cookstove type Number of cooking fires Wood name Season Size of cooking vessels Ignition method Cooking location Time of day	Cookstove application Cooking ingredients Cookstove type Number of cooking fires Wood name Season Ignition method Cooking location Time of day	Cookstove application Cookstove type Wood name Season Cooking location Time of day

Table 4
Household cooking tests for meals.

Test	Family																			Totals
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	
OCT	8	7	8	3	3	1	2	2	2											36
SCT			3		5				2	1		2	3	1	1	3	2	1		24
DCT	7	5	14	3	4		1	4	1		1	4		6			4	1	6	61
Totals	15	12	25	6	12	1	3	6	5	1	1	6	3	7	1	3	6	2	6	121

- The Session Cooking Test (SCT) measures the mass of fuel, the mass of all meal ingredients, and the mass of fuel remaining at the end of the cooking session. Demographic information and the number of people benefiting from the cookstove application is also recorded. A researcher is not present during the cooking session.
- The Daily Cooking Test (DCT) measures fuel consumption by weighing separate stacks of wood that have been set aside for each cooking event (i.e., one stack each for breakfast, lunch, dinner, and heating water). Each cooking event is a separate observation. The number of people benefiting from the cookstove application is also recorded. Although the DCT does not measure meal mass, the number of people eating is correlated with meal mass, and consequently can be used as a proxy for meal mass.

Categorical data were also recorded such as cookstove type, the number of cooking fires, and local wood names. As shown in Tables 4 and 5, a total of 155 household cooking tests were completed for 121 meals and 34 non-meals. Cooking studies focused on the five households from the planning study (families 1–5 in Table 4). Additional families were selected to gather information not available from the five primary families (e.g., specific cookstove and meal combinations) and to ensure that each stratum was represented by at least two families. Nineteen of the 60 families in the village were included. Cooking tests maintained the same cookstove operator for each household. It was impractical to obtain consecutive multi-day observations for each cook because women alternate cooking duties each day. Wood used in the cooking tests was gathered by the study participants. Emphasis was placed on studying energy use for cooking meals and heating water because these activities were observed to use the most wood during the planning study.

Energy use for each test was calculated from the mass of fuel consumed and the lower heating value of the fuel. Char produced during the test was counted as lost energy. Although the char is used later for making tea, it is not used as the primary fuel in any cookstove application that uses wood, and therefore it is lost as an energy source to those applications. Additionally, separating the char from pyrolized wood and unburned wood is a non-standardized process that can introduce significant error in energy calculations [34].

Table 5
Household cooking tests for non-meal cookstove applications.

Test	Cookstove application[a]						Totals
	WH	RP	MM	BK	RO	ST	
OCT	3	4	3			3	13
SCT	3	2		3	3		11
DCT	10						10
Totals	16	6	3	3	3	3	34

[a] Water heating (WH), roasting peanuts (RP), making medicine (MM), boiling shea kernel (BK), rendering shea oil (RO), steeping tea (ST).

3.3. Fuel tests

Wood is collected from dying trees or from the ground. Fruit-bearing trees and green wood are not used for fuel. Wood and charcoal species used in the village for fuel are shown in Table 6. Moisture analysis was completed for 35 wood samples and 12 charcoal samples taken during separate household cooking tests. Wood moisture content varies by season as shown in Table 7. Moisture content does not vary by species. Charcoal samples had a mean moisture content of 1.8% (range 1.0–3.2%) on an as-received basis with no seasonal trend in moisture content variation. Ultimate analysis, proximate analysis, and higher heating value (HHV) properties were determined for each wood species (Table 8). To simplify overall reporting of wood use, an equivalent as-received lower heating value of 14.8 MJ kg^{-1} was determined using a weighted average of woods and moisture contents that account for seasonal variation and preferred wood uses. This equivalent lower heating value was used to convert overall energy use to wood consumption. Similarly, a lower heating value of 29.7 MJ kg^{-1} was used for charcoal.

4. Results

Energy use data from cooking meals are first analyzed on a per meal basis. This is followed by an analysis of data from meal and non-meal cookstove applications on a daily basis. The dependent variable is energy use.

4.1. Energy use per meal

Regressions of energy use per meal were completed for 34 OCT and 24 SCT observations. Two OCT observations were dropped from the analysis because they had only one observation per meal type (i.e., stewed meat and steamed rice). Eight observations used more than one wood species and were cast as the wood species of the predominant wood consumed. Fuel size was not included in the analysis because a range of wood sizes were used, and hence wood size could not be represented by a single quantity. Cooking vessel size was not considered in the regression because multiple pots were used for some meals. Initial meal size was recorded in the OCT and SCT, thereby providing more observations for regression than final meal size which was recorded in the OCT only.

Multiple linear regression models of energy use per meal were tested with the continuous and categorical estimators given in Table 9. Categorical variables were cast as dummy variables. The Akaike information criterion (AIC) was used to guide estimator selection [37]. The criterion can be used as a guide to prevent over-fitting a regression with estimators that have little or no significance in the model. Regression models with a lower AIC are considered an improvement. Forward selection was used during regression analysis by first selecting the estimator that explained the most variation in the dataset, then adding additional estimators that explained the most residual variation until no further estimators were significant to the linear model. Table 10 lists models

Table 6
Wood and char species used for fuel in the village.

Scientific name[a]	Bamakan name	Uses
Carapa cf. *procera*	Jalla	Domestic cooking and heating
Combretum sp.	Damba	Domestic cooking and heating
Combretum sp.	Sow	Domestic cooking and heating
Detarium senegalense	Tamba	Domestic cooking and heating
Dialium guineense	Krekrete	Domestic cooking and heating; Baking;
Prosopis cf. *africana*	Guele	Charcoal production
Pterocarpus aff. *erinaceus*	Gendu	Domestic cooking and heating; Charcoal production[b]
Pterocarpus cf. *lucens*	Barra	Domestic cooking and heating
Cola nitida	Woro	Domestic cooking and heating
Char (*Prosopis* cf. *africana*)	Finfing	Blacksmithing
Char (*Pterocarpus* aff. *erinaceus*[b])	Finfing	Steeping tea[b]

[a] Scientific wood identification by light microscopic analysis is commonly accurate to the generic level (group of closely related species) and in rare instances accurate to the species level, particularly for tropical wood species [35].
[b] The char produced from multiple wood species is collected from domestic cooking and heating water. The *Pterocarpus* aff. *erinaceus* is the most common wood used.

pertinent to the study, sorted by AIC. Estimators that are statistically significant to at least the 90% confidence level are listed. Additional estimators are listed in Eq. (18) for the purpose of discussion.

The levels of a categorical variable with similar estimated coefficients were combined into a single dummy variable and tested again for significance. For example, estimated coefficients for the two breakfast porridges were similar and significantly different from the coefficients of the two meals with porridge and sauce. The two breakfast porridges were combined into one dummy variable, and the two meals with porridge and sauce were grouped into another dummy variable. Couscous was significantly different from the other meals and was represented as a third dummy variable. Interaction variables were not found to improve model fit. Table 10 lists all linear combinations of the parameters that were statistically significant in estimating cooking energy use. Although any one equation in Table 10 can be used to estimate energy use on a per meal basis, equations with a lower AIC and a higher R^2 will provide better estimates of energy use. The equations are provided to indicate the relative significance and relative strength of the estimators tested, and to serve as a guide for researchers designing cooking energy studies and programmatic cooking interventions.

Multiple regression analysis of data on a per meal basis indicated the following findings from the equations listed in Table 10:

- Of the two key continuous variables tested, the mass of total meal ingredients in Eq. (15) performed much better than family size in Eq. (21) at explaining variation in the dataset.
- The mass of dry ingredients in Eq. (8) is a better estimator of energy use than the total mass of dry ingredients and water in Eq. (15) or the mass of water in the meal Eq. (19). Interestingly, the mass of water is not a significant estimator if included in the regression with the mass of dry ingredients, indicating that the amount of water in the meal explains little, whereas the mass of dry ingredients explains much of the variation in energy use between tests.
- Model fit can be improved by including the meal type, Eqs. (4) and (7), and improved further by accounting for the ignition method, Eqs. (1) and (2). In all cases, meals with a sauce component use more energy to cook than other meals (32% increase using Eq. (4)). The dummy variable for couscous is not significant when using dry mass in Eq. (4), but is significant during a regression on total mass in Eq. (7). The difference in significance occurs because couscous is steamed, and the total initial mass of couscous is only the dry ingredients, whereas the total mass of other meals includes dry and wet ingredients.
- Including family size (Eq. (3)) in the regression with the mass of dry ingredients and meal type (Eq. (4)) provides a small improvement in model fit. However, the low significance of the family size estimate coefficient indicates that little variability is explained by family size after accounting for other factors; family size is not significant with any other regression that includes mass.
- Creating separate continuous variables for the dry ingredient mass and total mass of each meal type in Eqs. (9) and (10), respectively, improves model fit over the regression with no differentiation between meals in Eqs. (8) and (15). However, the regression including dry ingredients (Eq. (9)) receives a slightly higher AIC because the additional explanatory power does not offset the penalty of adding more estimators to the model.
- There is little evidence that cookstove type affects energy use after accounting for differences in meal size. Using the three-stone fire as the reference variable, only one stove has a statistically significant effect on energy use, as shown in Eqs. (6), (11), (14) and (18), but only at the lowest confidence level of 90%; the locally-made low thermal capacity cookstove showed an increase in wood consumption of 28% (Eq. (18)). The manufactured metal cookstove decreased wood consumption by 25% but not at a statistically significant level (Eq. (18)).
- The use of burning embers as an igniter is significant in Eqs. (1), (2), (5), (12) and (16) and reduces overall energy use. This is partly attributed to the dataset representation that does not account for the energy content in the charcoal. However, the energy content of the estimated coefficient equates to 270 g of charcoal, which is two- to four-fold higher than the observed mass of charcoal used to start a fire, suggesting that the use of burning charcoal embers as an igniter may reduce overall energy use per meal.
- Cooking on two fires increases the amount of energy use per meal (Eqs. (11), (13) and (20)) by approximately 26% (Eq. (13)).
- The number of standard adult equivalents showed no improvement over family size in explaining energy use. This is because the number of standard adult equivalents had a high correlation with family size ($R^2 = 0.9847$). This indicates that demographic information provides no additional useful information for explaining energy use per meal during regression analysis.
- Test type (OCT and SCT) had no significance in explaining energy use in any of the regressions listed. Either method can be used interchangeably without statistically affecting the results and conclusions.
- Other variables that showed no significance as estimators after accounting for other factors included wood moisture content, wood species, cookstove operator, season, grain type, sauce type, and mealtime of day.

Table 7
Seasonal variation in wood moisture content on an as-received basis (wt %) [36].

Month samples acquired	Weather description	Mean (range)	Number of samples
May	Hot and dry	10.9 (10.2–12.2)	7
August	Temperate and rainy	18.3 (13.6–43.1)	15
December	Cool and dry	7.7 (6.2–12.9)	13

Table 8
Proximate analysis, ultimate analysis, and higher heating value (HHV) tests for wood and charcoal samples. Values reported on a dry, ash-free basis [36].

Scientific name	Ash (wt %)	Volatiles (wt %)	Fixed carbon (wt %)	C (wt %)	H (wt %)	O (wt %)	N (wt %)	S (wt %)	HHV (MJ kg^{-1})
Carapa cf. *procera*	1.83	87.77	12.23	51.80	5.87	41.58	0.74	0.01	20.2
Combretum sp. (Damba)	3.18	84.96	15.04	48.46	6.15	44.64	0.69	0.06	18.2
Combretum sp. (Sow)	3.78	86.41	13.59	53.08	6.08	40.37	0.46	0.01	19.2
Detarium senegalense	2.29	88.11	11.89	50.12	6.12	43.15	0.56	0.05	20.0
Dialium guineense	3.16	85.03	14.97	48.90	6.20	44.66	0.23	0.01	19.1
Prosopis cf. *africana*	1.98	72.82	27.18	53.11	5.64	40.71	0.52	0.02	20.6
Pterocarpus aff. *erinaceus*	1.09	84.78	15.22	48.76	6.14	45.06	0.02	0.02	18.9
Pterocarpus cf. *lucens*	0.75	85.43	14.57	49.15	5.99	44.64	0.20	0.02	18.5
Char (*Prosopis* cf. *africana*)	12.99	9.26	90.74	82.02	3.94	13.42	0.61	0.01	33.6
Char (*Pterocarpus* aff. *erinaceus*)	5.71	12.78	87.22	90.78	1.78	6.64	0.75	0.05	32.4

4.2. Energy use per day

To determine daily cooking energy use for a family, the results of tests were equated to a daily basis. This in turn can be used to determine cooking energy use for the entire village over a longer time period. Meal observations were not always available for all three meals over a one-day period due to various cooking responsibility patterns. Data available from the OCT and SCT were aggregated into nine full-day meal observations (27 of 58 observations), and data from the DCT were aggregated into 12 full-day meal observations (36 of 61 observations). Combining data from the OCT and SCT with data from the DCT reduced the explanatory power of linear models; hence, the datasets were not aggregated. Data for water heating and steeping tea were left unchanged, and data for making medicine and roasting peanuts were equated to a per day basis because these cookstove applications occurred less frequently than every day. Data from all three cooking tests were used.

Simple linear regressions were performed on energy use for cooking meals, roasting peanuts, and heating water. Due to the low number of observations, the mean energy use was calculated for steeping tea and making medicine. Results of meal and non-meal cooking analysis on a daily basis are shown in Table 11. Family size and the mass of meal ingredients explain a similar amount of variation in the test data obtained from cooking meals in Eqs. (22)–(25). For the regressions on family size, estimated coefficients were similar if a researcher was present at the meal or present before and after the meal (Eq. (23)), but differed if a researcher was not present near mealtime (Eq. (22)). The DCT does not have a researcher present at or near mealtime and provides higher energy use estimates for families larger than four people; DCT estimates are 22% higher for the average family size of 12.8, and 46% higher for a family of 40 people. This could be attributed to wood consumption that is not observed, or to cooks decreasing wood use when a researcher is present. Although Eq. (22) has a higher correlation with family size, Eq. (23) is preferred because there is a reduced risk of data contamination when a researcher observes all wood consumption. Regressions on a per day basis did not include cookstove type because women often used multiple types of cookstoves during the day. As in the regressions on a per meal basis, the number of standard adult equivalents was not used because it did not improve model fit. For the regressions of energy use for heating water, the regression on family size in Eq. (26) does not perform as well as the regression on the mass of water in Eq. (27). The two regressions of energy use for roasting peanuts explained a similar amount of variation in test data, Eqs. (28) and (29). Energy use for making medicine and steeping tea are determined based on the rate at which a family makes medicine (Eq. (30)) and steeps tea (Eq. (31)). Energy use for shea processing was not equated to a per day basis because it is completed only a few times each year. Mean values for boiling the shea kernel and rendering the shea oil are 6.0 MJ kg^{-1} kernel ($\sigma = 2.1$, 3 obs.) and 25.6 MJ kg^{-1} rendered oil ($\sigma = 9.0$, 3 obs.), respectively. Using a mass fraction of 8.7% of rendered oil to whole kernel, a total of 94 MJ of energy (6.4 kg of as-received wood) is used to process 1 kg of oil on a cookstove.

As shown in Fig. 2, Eqs. (22)–(31) can be used to estimate daily household energy use for cookstove applications. Eqs. (22)–(25) present four different ways to estimate energy use for cooking meals. Eqs. (26) and (27) present two different ways to estimate energy use for heating water. Eqs. (28) and (29) present two

Table 9
Estimators tested in multiple regression models of energy use per meal.

Continuous variables	Categorical variables	Levels of categorical variables
Number eating	Cookstove type	Three-stone fire, gakourouwana, low thermal capacity, hand-crafted metal, manufactured metal
Number standard adult equivalent[a]		
Mass water	Meal type	Breakfast porridge (thin), breakfast porridge (thick), meal porridge (thin) with sauce, meal porridge (thick) with sauce, couscous
Mass dry ingredients		
Mass total ingredients (initial)	Meal time of day	Breakfast, lunch, dinner
Wood moisture content	Grain type	Corn, millet, rice
	Sauce type	Leaves, peanut, okra
	Cookstove operator	One operator for each of the 17 families who participated in OCT or SCT tests
	Number of cooking fires	One, two
	Ignition method	Straw, burning embers, plastic
	Wood species	*Carapa* cf. *procera*, *Combretum* sp. (Damba), *Combretum* sp. (Sow), *Detarium senegalense*, *Pterocarpus* aff. *erinaceus*, *Pterocarpus* cf. *lucens*
	Season	Hot and dry, temperate and rainy, cool and dry
	Test type	OCT, SCT

[a] Modifies the number of people eating based on demographic information: children 0–14 yr (0.5), females over 14 yr (0.8), males 15–59 yr (1.0), males over 59 yr (0.8) [21,22].

Table 10
Multiple regression models of energy use per family per meal.

Estimators of MJ fam^{-1} meal^{-1}		R^2	AIC
$19.74^{***} + 7.23^{***} m_{dry} + 10.10^{**} M_{sau} - 8.16^{**} I_{char}$	(1)	0.7188	430.5
$14.83^{***} + 2.04^{***} m_{tot} + 12.56^{***} M_{sau} + 13.01^{*} M_{cous} - 8.69^{**} I_{char}$	(2)	0.7100	434.2
$10.20^{**} + 6.15^{***} m_{dry} + 0.47^{\dagger} n_p + 10.17^{**} M_{sau}$	(3)	0.6898	436.1
$14.49^{***} + 7.31^{***} m_{dry} + 9.31^{**} M_{sau}$	(4)	0.6690	437.9
$20.59^{***} + 9.16^{***} m_{dry} - 7.41^{*} I_{char}$	(5)	0.6606	439.3
$7.32^{*} + 2.19^{***} m_{tot} + 11.76^{***} M_{sau} + 11.84^{*} M_{cous} + 7.93^{\dagger} S_{LTC}$	(6)	0.6733	441.1
$9.33^{**} + 2.04^{***} m_{tot} + 11.95^{***} M_{sau} + 13.31^{*} M_{cous}$	(7)	0.6537	442.5
$15.74^{***} + 9.10^{***} m_{dry}$	(8)	0.6193	444.0
$16.91^{***} + 8.21^{***} m_{dry,gra} + 10.87^{***} m_{dry,sau} + 5.01^{*} m_{dry,cous}$	(9)	0.6434	444.2
$14.31^{***} + 1.53^{**} m_{tot,gra} + 4.97^{***} m_{tot,sau} + 6.07^{*} m_{tot,cous}$	(10)	0.6334	445.8
$10.35^{**} + 2.35^{***} m_{tot} + 7.65^{*} N_f + 8.82^{\dagger} S_{LTC}$	(11)	0.6172	448.3
$18.79^{***} + 2.45^{***} m_{tot} - 8.17^{*} I_{char}$	(12)	0.5975	449.2
$13.00^{***} + 2.15^{***} m_{tot} + 8.06^{*} N_f$	(13)	0.5924	450.0
$10.73^{**} + 2.61^{***} m_{tot} + 9.59^{\dagger} S_{LTC}$	(14)	0.5770	452.1
$13.65^{***} + 2.41^{***} m_{tot}$	(15)	0.5475	454.0
$15.13^{**} + 0.99^{***} n_p + 19.81^{***} M_{sau} - 6.41^{\dagger} I_{char}$	(16)	0.5763	454.2
$7.10^{\dagger} + 1.16^{***} n_p + 20.75^{***} M_{sau} + 10.10^{\dagger} M_{cous}$	(17)	0.5700	455.1
$10.77^{*} + 2.66^{***} m_{tot} + 1.69 S_{GK} + 9.32^{\dagger} S_{LTC} - 1.58 S_{HCM} - 8.12 S_{MM} - 2.53 S_{MULT}$	(18)	0.5969	457.3
$15.95^{***} + 2.81^{***} m_w$	(19)	0.4487	465.5
$11.19^{*} + 1.33^{***} n_p + 15.72^{***} N_f$	(20)	0.4430	468.1
$16.30^{**} + 1.37^{***} n_p$	(21)	0.2484	483.5

Significance for each estimator is denoted by *** <0.001; ** <0.01; * <0.05; † <0.1 or blank for no significance. Lower case letters represent continuous variables with units specified below; upper case letters represent dummy variables and have no units. Regressions were completed over 58 observations. Variables listed: m_{tot} is the total initial mass of dry ingredients and water in kg, m_w is the mass of water in kg, m_{dry} is the mass of dry ingredients in kg, m_{gra} is the mass of meal with grain in kg, m_{sau} is the mass of meal with sauce in kg, m_{cous} is the mass of meal with couscous in kg, n_p is the number of people in a family in capita, N_f is a dummy variable for the number of fires that is equal to one when there are two active fires for the meal, I_{char} is a dummy variable for use of burning embers as an ignitor, M_{sau} is a dummy variable for meal with sauce, M_{cous} is a dummy variable for meal with couscous, S_{GK} is a dummy variable for use of a gakourouwana cookstove, S_{LTC} is a dummy variable for use of a low thermal capacity cookstove, S_{HCM} is a dummy variable for use of a hand-crafted metal cookstove, S_{MM} is a dummy variable for use of a manufactured metal cookstove, and S_{MULT} is a dummy variable for use of two types of cookstove.

Table 11
Statistical models of energy use per family per day.

Cookstove application	Estimators of MJ fam^{-1} day^{-1}		Comments	Test type(s)
Cooking meals	$42.61^{*} + 6.56^{***} \times n_p$	(22)	Regression, $R^2 = 0.8067$, 12 obs.	DCT
	$53.51^{**} + 3.90^{**} \times n_p$	(23)	Regression, $R^2 = 0.7247$, 9 obs.	OCT, SCT
	$50.90^{**} + 2.01^{**} \times m_{tot}$	(24)	Regression, $R^2 = 0.7662$, 9 obs.	OCT, SCT
	$31.60 + 10.83^{**} \times m_{dry}$	(25)	Regression, $R^2 = 0.7281$, 9 obs.	OCT, SCT
Heating water	$9.70 + 2.64^{***} \times n_p$	(26)	Regression, $R^2 = 0.6502$, 16 obs.	OCT, SCT, DCT
	$13.37^{*} + 0.43^{**} \times m_w$	(27)	Regression, $R^2 = 0.8898$, 6 obs.	OCT, SCT
Roasting peanuts	$-0.911 + 0.446^{**} \times n_p$	(28)	Regression, $R^2 = 0.8660$, 6 obs.	OCT, SCT
	$\left(9.92^{\dagger} + 4.21^{**} \times m_{pea}\right) \times r_{pea}$	(29)	Regression, $R^2 = 0.8766$, 6 obs.	OCT, SCT
Making medicine	$18.3 \times r_{med}$	(30)	Mean, $\sigma = 8.3$, 3 obs.	OCT
Steeping tea	$1.57 \times r_{tea}$	(31)	Mean, $\sigma = 0.32$, 3 obs.	OCT

Significance for each estimator is denoted by *** <0.001; ** <0.01; * <0.05; † <0.10. Variables are: n_p is the number of people in a family in capita, m_{tot} is the total mass of dry ingredients and water for the entire family in kg, m_{dry} is the mass of dry ingredients for the entire family in kg, m_w is the mass of water heated for the entire family in kg, r_{pea} is the rate of roasting peanuts per day in times day^{-1}, r_{med} is the rate of making medicine per day in times day^{-1}, r_{tea} is the rate of steeping tea per day in times day^{-1}.

different ways to estimate energy use for roasting peanuts. A single method is presented for estimating energy use for making medicine and steeping tea, Eqs. (30) and (31) respectively. As shown in Fig. 2, one method is selected for each cookstove application and then applied to each family in the village. The results are then added to determine total village energy use. Thus the methods for gathering data for a study of village energy can be designed in several ways. The methodology is applicable to any day of the year, noting that in the rainy season shea processing must be included. Energy use for shea processing is calculated using data on the rate

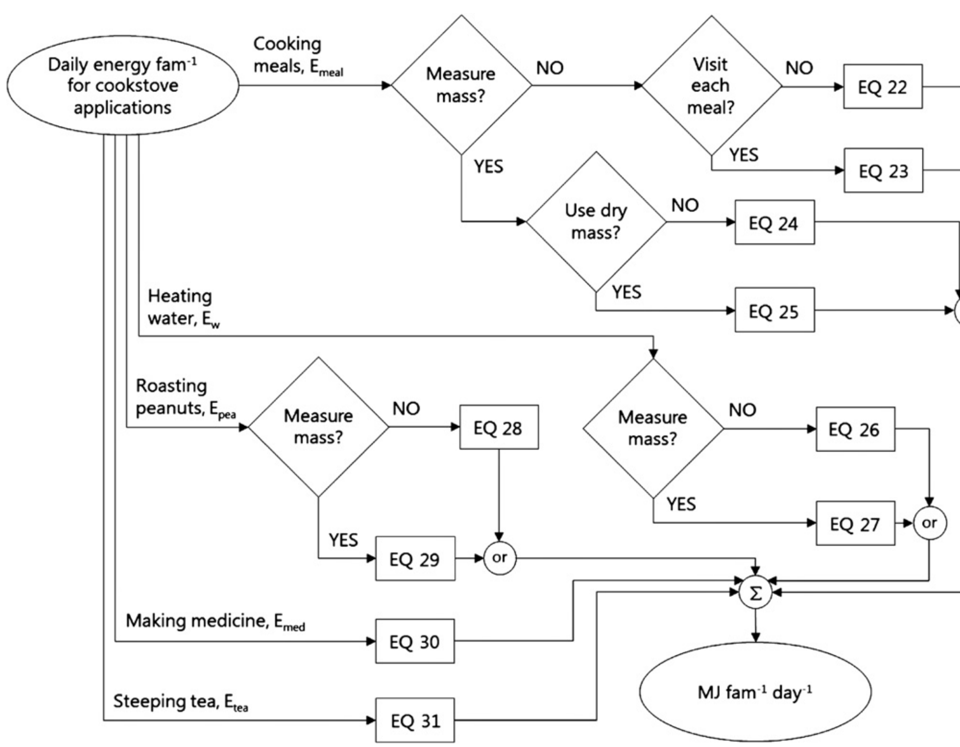

Fig. 2. Estimation methodologies for daily household energy use for domestic cookstove applications. Shea processing not shown.

of shea processing for each cook in a family and the mean energy use for shea processing introduced earlier. Using the mean energy use for processing shea and the mass of shea kernel and oil observed in tests, the amount of energy used to process shea from kernel to oil equates to 30.2 kg of wood per month, assuming the woman processes shea once per month.

The total error in estimating daily household energy use can be represented as the weighted sum of errors across all cooking activities by multiplying the estimation error for each cooking activity with its fractional contribution to cooking energy use. First, the estimate error, err_i, is calculated for each cooking observation using Eq. (32). The observed energy use, E_i, is compared to the estimated energy use, $\widehat{E}_i$, using the appropriate equations for each cooking activity (Eqs. (23), (26), (28), (30), and (31)). Table 12 provides the minimum, maximum, and average errors for each cooking activity. The weighted sum of these errors indicates that the estimation of daily household energy use has an average error of 19.1%, a minimum error of 1.9%, and a maximum error of 55.6%. Although the estimates for making medicine have the greatest error, the contribution to total energy use is small. Cooking meals and heating water estimates contribute to 92.3% of total error. Efforts to improve estimation accuracy of daily household energy use should concentrate on reducing the error of energy use estimates for cooking meals and heating water.

$$\mathrm{err}_i = \frac{\left|E_i - \widehat{E}_i\right|}{E_i} \tag{32}$$

4.3. Discussion of results

The results from multiple regression analysis of energy use for cooking meals indicate that meal type, the total meal mass, the mass of dry ingredients, family size, the use of burning embers as an igniter, and the number of cooking fires are significant factors in explaining energy use per meal. Only one cookstove's energy impact is significantly different than the other four cookstoves, and at the lowest level of confidence, suggesting that cookstove type has little significance in explaining cooking energy use after accounting for other factors. Variables that showed no significance in explaining meal energy use after accounting for other factors included standardized adult equivalent, mass of water, wood moisture content, wood species, cookstove operator, season, grain type, sauce type, meal time of day, or test type (OCT or SCT).

Single regression analysis of energy use for cooking meals on a per day basis showed that the number of people eating, the total meal mass, or the mass of dry ingredients were similarly good estimators. This contrasts with regressions on a per meal basis in which the number of people eating was a poor estimator of energy use. One cause for this may be the reduced variation in per capita food consumption on a daily basis compared to a per meal basis, as indicated by the coefficient of variation of 0.31 on a daily basis and 0.55 on a meal basis. The coefficient of variation is a normalized version of the standard deviation that adjusts for different magnitudes in the means. When comparing the regressions on a per meal basis and on a per day basis, no regression of energy use on a per meal basis explains more variability than any regression on a daily basis. However, the simple linear regressions on a daily basis use a coarser dataset and fewer factors to explain energy use compared to multiple regression analysis on a per meal basis. Thus the daily regressions do not provide an understanding of the intra-day or intra-meal drivers of fuel consumption.

There is strong evidence that daily energy use per capita for cooking meals varies by family size based upon an analysis of variance testing to compare energy use per capita across the five strata ($p = 6.21 \times 10^{-5}$, the probability that per capita fuel usage is equivalent across all strata). Although total village energy use can be expressed in energy per capita, that statistic should be used with caution for estimating family energy use, or in comparing energy use between families. For example, the regression equation on the mean family size estimates energy use per capita for cookstove applications at 20.6 MJ cap^{-1} day^{-1} and 10.5 MJ cap^{-1} day^{-1} for a family of 5 and 20 people, respectively. The village average of 12.3 MJ cap^{-1} day^{-1} significantly underestimates wood consumption for a small family and overestimates it for a large family because it does not represent the economies of scale with large cooking fires. The observation that per capita energy consumption for cooking and heating water drops by roughly half as family size increases is consistent with recent observations of fuelwood consumption in Cambodia [38].

Regressions of energy use for hot water indicated that the mass of hot water explained more variation than the number of people bathing. For roasting peanuts, the regression using the mass of peanuts or the regression on the number of people eating explained a similar amount of variation in the observed data. Other findings from the analysis indicate

- Estimated coefficients differ between the regressed equations for cooking meals, roasting peanuts, and heating water. This suggests that the data should be analyzed separately rather than regressed across all cookstove applications.
- The magnitude of the estimated coefficients indicated that cooking meals and heating water use the majority of energy. As such, programs to reduce wood energy use should concentrate on these cookstove applications.
- Regressions of energy use for cooking meals differed if the researcher measured energy use immediately following the meal (OCT or SCT) or at the end of the day (DCT). This could be attributed to wood consumption that is not observed, or to cooks decreasing wood use when a researcher is present.
- A reduction in the size of grain flour is a common method to reduce cooking time and subsequently wood consumption. However, there is no evidence this will reduce energy use in this village. The two breakfast meal types show no statistical difference in energy use although grain flour diameters differ by approximately two-fold. While smaller particles cook faster, families cook each meal to a thickness based on culturally defined preferences.
- There is no evidence that energy use for cooking meals varies by season. Approximately one-half of the village uses different grains for preparing porridge in different seasons, but only a few families change the types of meals prepared. Energy used for making medicine and making tea is defined by a rate of use that varies by season, and there is evidence from interviews that the rate of heating water varies by season based upon family preferences.
- There is strong evidence of cookstove stacking in that no improved cookstove completely displaces the traditional three-stone fire or gakourouwana cookstove. In nearly all cases,

Table 12
Error in daily household cooking energy use estimation.

Cooking activities[a]	Average error (range) (%)	Contribution to total energy use (%)	Contribution to total error (%)
Cooking meals	12.8 (0.5–45.4)	65.8	44.2
Heating water	32.9 (3.8–80.7)	28.0	48.1
Roasting peanuts	15.2 (6.4–35.9)	3.1	2.5
Making medicine	47.2 (12.3–102.6)	1.6	4.1
Steeping tea	14.9 (5.8–20.2)	1.5	1.1
Daily energy	19.1 (1.9–55.6)	100	100

[a] Shea processing is not included in daily energy use estimation.

a woman with more than one cookstove used multiple cookstoves. Even women with improved metal cookstoves still used traditional fires. This user behavior when considered along with the number of cookstove applications and range in cooked mass suggests that multiple cookstove options may be needed to completely displace traditional fires.

- Of the three tests introduced to examine cookstove energy use, the DCT provides the least time-intensive method to measure fuel consumption, and subsequently needs the least time to create regressions for estimating fuel consumption from demographic survey data. However, only the SCT and OCT provide data on the intra-day or intra-meal factors that affect fuel consumption. Further, only the OCT involves direct observation of the cooking activity to describe cooking behavior and other qualitative factors affecting fuel consumption.

5. Conclusions and future work

This study identified six factors that explained fuel consumption for cooking in a rural West African village. These factors are the type of cookstove application, family size, total mass of wet and dry ingredients, mass of dry ingredients, the use of burning embers as an igniter, and the number of fires used during a cooking event. In addition, the type of cookstove had limited impact on fuel consumption; this factor had the lowest level of significance (90%) after accounting for other factors for one type of stove. Analysis of the results indicated that other stove types may impact fuel consumption, but their effect was not statistically significantly in this study. In addition, the analysis showed that different types of cookstove applications should not be aggregated into a single model of cooking energy use because of the reduced explanatory power of the aggregated model. Instead, each cookstove application should be examined separately. In noting that cooking meals (65%) and heating water (27%) account for nearly all cookstove energy use, those two applications could be used to approximate total cooking energy with minimal error. The total village cookstove energy use of 234 tons wood yr^{-1} would therefore be approximated as 215 tons wood yr^{-1} if including only cooking meals and heating water in the estimation. The observation that energy use for heating water is roughly one-half the energy use for cooking food is consistent with recent observations of household fuelwood use in rural Cambodia [38]. Specifically the energy use for heating water was 43% and 54% of energy use for cooking in this study and in rural Cambodia, respectively. In addition, it is consistent with household energy studies conducted on a national level in Mexico that included a wide range of incomes and sources of household energy [39]. This study reported that the household energy used for heating water was 56% of the energy used for cooking in Mexico.

The use of burning embers as an igniter was found to decrease total energy used for cooking by a conservative estimate of 10% after accounting for energy from the char. Assuming that an open cooking fire is approximately 15% efficient, the use of burning embers is equivalent to a 1.7% increase in cooking efficiency. Additional studies are required to understand the underlying causes of this observation.

There was strong evidence of “stove stacking” in which improved stoves were used as additional cooking resources rather than as a replacement for traditional open-fire cooking methods. Within the study village, 52% of cooks used only one cookstove, 36% used two cookstoves, and 12% used three or more. This finding is consistent with other recent studies. In Mexico it was reported that eight months following the introduction of an improved stove 15% of households reported exclusive use of the improved stove while nearly 60% of household reported some or exclusive use [16]. As noted by Ruiz-Mercado et al. [40], the use of multiple fuel and cooking devices has a significant impact on the adoption of improved stoves.

Additional studies in West Africa are planned to validate and extend the current study. The current results can be used to design rural energy studies that measure cookstove energy use, estimate cookstove energy use, or assess the impact of programmatic household energy interventions. Because this study involves a small number of improved cookstoves in only one village, additional studies are needed of larger cookstove programs. Moreover, additional studies of household cookstove energy use are needed from other world regions.

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References

[1] Manibog FR. Improved cooking stoves in developing countries: problems and opportunities. Annu Rev Environ Resour 1984;9(1):199–227.
[2] Wickramasinghe A. Gender and health issues in the biomass energy cycle: impediments to sustainable development. Energy Sustainable Dev 2003;7(3): 51–61.
[3] Ramanathan V, Carmichael G. Global and regional climate changes due to black carbon. Nat Geosci 2008;1:221–7.
[4] Pohekar SD, Ramachandran M. Multi-criteria evaluation of cooking devices with special reference to utility of parabolic solar cooker (PSC) in India. Energy 2006;31(8–9):1215–27.
[5] Champier D, Bédécarrats JP, Kousksou T, Rivaletto M, Strub F, Pignolet P. Study of a TE (thermoelectric) generator incorporated in a multifunction wood stove. Energy 2011;36(3):1518–26.
[6] Dufo-López R, Zubi G, Fracastoro GV. Tecno-economic assessment of an off-grid PV-powered community kitchen for developing regions. Appl Energy 2012;91(1):255–62.
[7] van Groenendaal W, Gehua W. Microanalysis of the benefits of China’s family-size bio-digestors. Energy 2010;35(11):4457–66.
[8] Reddy AKN, Smith KR, Willams RH. Rural energy in developing countries [Ch. 10]. In: Goldemberg J, editor. World energy assessment: energy and the challenge of sustainability. New York, USA: United Nations Development Programme. p. 367–89. Available from: www.undp.org/content/dam/aplaws/publication/en/publications/environment-energy/www-ee-library/sustainable-energy/world-energy-assessment-energy-and-the-challenge-of-sustainability/World%20Energy%20Assessment-2000.pdf; 2000 [accessed 05.08.12].
[9] Johnson NG, Bryden KM. Energy supply and use in a rural west African village. Energy 2012;43(1):283–92.
[10] Khuman YSC, Pandey R, Rao KS. Fuelwood consumption patterns in Fakot watershed, Garhwal Himalaya, Uttarakhand. Energy 2011;36(8):4769–76.
[11] Jetter JJ, Kariher P. Solid-fuel household cook stoves: characterization of performance and emissions. Biomass Bioenergy 2009;33:294–305.
[12] MacCarty N, Still D, Ogle D. Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. Energy Sustainable Dev 2010;14:161–71.
[13] Bailis R, Berrueta V, Chengappa C, Dutta K, Edwards R, Masera O, et al. Performance testing for monitoring biomass stove interventions: experiences of the household energy and health project. Energy Sustainable Dev 2007; 11(2):57–70.
[14] Smith KR, Dutta K, Chengappa C, Gusain PPS, Masera O, Berrueta V, et al. Monitoring and evaluation of improved biomass cookstove programs for indoor air quality and stove performance: conclusions from the household energy and health project. Energy Sustainable Dev 2007;11(2):5–18.
[15] Granderson J, Sandhu JS, Vasquez D, Ramirez E, Smith KR. Fuel use and design analysis of improved woodburning cookstoves in the Guatemalan Highlands. Biomass Bioenergy 2009;33:306–15.
[16] Pine K, Edwards R, Masera O, Schilmann A, Marrón-Mares A, Riojas-Rodrígeuz H. Adoption and use of improved biomass stoves in rural Mexico. Energy Sustainable Dev 2011;15(2):176–83.
[17] Jan I. What makes people adopt improved cookstoves? Empirical evidence from rural northwest Pakistan. Renewable Sustainable Energy Rev 2012; 16(5):3200–5.

[18] Lewis JJ, Pattanayak SK. Who adopts improved fuels and cookstoves? A systematic review. Environ Health Perspect 2012;120(5):637–45.
[19] Bailis R. The controlled cooking test (version 2.0) (Partnership for Clean Indoor Air). London, UK: Household Energy and Health Programme, Shell Foundation. Available from:, www.pciaonline.org/files/CCT_Version_2.0_0.pdf; 2004 [accessed 05.08.12].
[20] Bailis R, Smith KR, Edwards R. Kitchen performance test (version 3.0). London, UK: Household Energy and Health Programme, Shell Foundation. Available from: www.pciaonline.org/files/KPT_Version_3.0_0.pdf; 2007.
[21] Baldwin SF. Biomass stoves: engineering design, development, and dissemination [dissertation]. Princeton (NJ): Princeton University Center for Energy and Environmental Studies; 1987.
[22] Joseph S. Guidelines for planning, monitoring and evaluating cookstove programmes. Community forestry field manual no. 1. Rome, Italy: Food and Agricultural Organization, United Nations. Available from:, www.fao.org/docrep/u1310e/U1310e02.htm; 1990 [accessed 05.08.12].
[23] Howes M. Rural energy surveys in the third world: a critical review of issues and methods. Ottawa, ON, Canada: International Development Research Centre Document IDRC-MR107e. Available from: idl-bnc.idrc.ca/dspace/handle/10625/4257; 1985 [accessed 05.08.12].
[24] Geller HS. Fuel efficiency and performance of traditional and innovative cookstoves. Proc Indian Sci Eng Sci 1982;5(4):373–93.
[25] Reddy AKN. Rural energy consumption patterns: a field study. Biomass 1982; 2(4):255–80.
[26] Adkins E, Tyler E, Wang J, Siriri D, Modi V. Field testing and survey evaluation of household biomass cookstoves in rural sub-Saharan Africa. Energy Sustainable Dev 2010;14(3):172–85.
[27] Miah MD, Rashid HA, Shin MY. Wood fuel use in the traditional cooking stoves in the rural floodplain areas of Bangladesh: a socio-environmental perspective. Biomass Bioenergy 2009;33:70–8.
[28] Biswas WK, Lucas NJD. Energy consumption in the domestic sector in a Bangladesh village. Energy 1997;22(8):771–6.
[29] Hosier RH. Domestic energy consumption in rural Kenya: results of a nationwide survey. In: Barnes C, Ensminger J, O'Keefe P, editors. Wood, energy, and households: perspectives on rural Kenya. Stockholm, Sweden: Beijer Institute, Royal Swedish Academy of Sciences and Uppsala (Sweden): Scandinavian Institute for African Studies; 1984. p. 14–59.
[30] World bank [internet]. Washington DC, USA: World Bank Rural Population Indicators. Available from: data.worldbank.org/indicator/SP.RUR.TOTL; 2012 [cited 2012 May 2] [accessed 05.08.12].
[31] (United Nations Development Programme) Klugman J. The real wealth of nations: pathways to human development. Human Development Report 2010. New York, USA: Palgrave MacMillan. Available from:, hdr.undp.org/en/reports/global/hdr2010/; 2010 [accessed 05.08.12].
[32] SIE-Mali. Système d'information énergétique du Mali Rapport 2007. Bamako, Mali: Minstere de l'energie et de l'eau, Republique du Mali. Available from: www.dnemali.org//upload_document/Rapport_SIE_2007.pdf; 2007 [accessed 05.08.12].
[33] World Health Organization [internet]. Report of Mali. Geneva, Switzerland: World Health Survey Results: Regional Office for Africa, Mali. Available from: www.who.int/healthinfo/survey/whsmli-mali.pdf [accessed 05.08.12].
[34] Taylor III RP. The uses of laboratory testing of biomass cookstoves and the shortcomings of the dominant U.S. protocol [master' thesis]. Ames, IA, USA: Iowa State University; 2009.
[35] Wiedenhoeft AC. The limits of scientific wood identification. Prof Appraisers Inf Exchange 2006;4(2):16.
[36] ASTM E870. Annual book of ASTM standards 11.06. West Conshohocken, PA, USA: ASTM International; 2009.
[37] Akaike H. A new look at the statistical model identification. IEEE Trans Autom Control 1974;AC-19(6):716–23.
[38] San V, Spoann V, Dalin L, Chheng NV. Fuelwood consumption patterns in Chumriey Mountain, Kampong Chhnang Province, Cambodia. Energy 2012; 44(1):335–45.
[39] Rosas-Flores JA, Gálvez DM. What goes up: recent trends in Mexican residential energy use. Energy 2010;35(6):2596–602.
[40] Ruiz-Mercado I, Masera O, Zamora H, Smith KR. Adoption and sustained use of improved cookstoves. Energy Policy 2011;39(12):7557–66.