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Village energy system dynamics of an isolated rural West African village

Nathan Gregory Johnson
Iowa State University

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Nathan Gregory Johnson

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Major: Mechanical Engineering

Program of Study Committee:
Kenneth Mark Bryden, Major Professor
Arne Hallam
Song-Charng Kong
Richard LeSar
Erin MacDonald

Iowa State University

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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ABSTRACT

This thesis examines the detailed energy system dynamics of an isolated rural agricultural village in West Africa. Every family lives on subsistence agriculture and there is no access to the electric grid. The study is based on a planning visit followed by three one-month studies in different seasons of a one-year period. Methods and findings are presented in three parts: (1) the overall dynamics of village energy supply and use for a one-year period, (2) the factors that influence fuel use for domestic cookstove applications, and (3) an assessment of the costs and benefits of various energy options for meeting domestic cooking needs. Wood and electricity account for 94% and less than 1% of village energy supply, respectively, yet both provide vital needs—cooked meals, hot water, warmth, clean water, lighting, and power for small electronics. The need for small-scale electricity is so great that the 21,000 disposable batteries purchased each year account for 65% of all domestic energy expenditures. Three-quarters of the annual village wood supply is burned within domestic cooking stoves. Multiple regression analysis was used to identify six factors that significantly impacted cooking energy use. These included the cookstove application, family size, total mass of wet and dry ingredients, mass of dry ingredients, use of burning embers as an igniter, and the number of fires used during a cooking event. Analysis indicated that cookstove type may affect fuel consumption but the effect was not statistically significant. Strong evidence was found of "stove stacking" in which improved stoves are used as additional cooking resources rather than a replacement for existing stoves. Sixty combinations of domestic cooking options were compared based on program cost and expected reduction in fuelwood use. Annualized capital costs ranged from zero to US$3,130 per year for reductions in wood use between 10.0% and 86.8% of the 234 metric tons of fuelwood used annually for cooking.

CHAPTER 1

INTRODUCTION

Over three billion people live in rural areas of low- and middle-income countries [World Bank 2011a]. Much of this population lives in isolated agricultural villages that have limited access to energy and energy technologies. Because of this, rural households have many unmet energy needs, including cooking, lighting, heating, transportation, and telecommunication. Worldwide, rural households account for 85% of the 1.4 billion people lacking access to electricity, and they account for 83% of the 2.7 billion people who rely on biomass fuels for cooking [International Energy Agency 2010].

Addressing these unmet rural energy needs is fundamental to improving the quality of life in developing countries. Rural energy development can save time, improve health, and help preserve the environment [Bond and Sun 2005, Bruce et al. 2011, Jetter and Kariher 2009, Madubansi and Shackleton 2006]. There are many examples. Clean energy for cooking reduces indoor air pollution, a leading cause of mortality for women and children. Lighting allows children to study at night and adults to run household businesses. Heating provides a family with warmth during the cold season. Transportation provides access to market-based products and allows access to basic livelihood services such as health care. Telecommunication enables local artisans and businesses to check market prices and plan deliveries. Further, the benefits of improved access to energy and energy technologies extend beyond the needs they directly address. A report by the United Nations has commented that rural development and poverty reduction strategies can be hindered without sufficient access to modern energy sources.

> "Insufficient access to modern sustainable energy services hampers major structural changes in rural economies necessary for enhancing income generating activities. The lack of modern sustainable energy supply hinders rural development, thereby also limiting poverty reduction efforts" [UN 2003].

Many organizations have worked to provide energy solutions for the rural poor. Water pumps, lights, cookstoves, and many other technologies have been implemented in rural villages. But too often these technologies fail. For example, an estimated 30% of water pumps installed in sub-Saharan Africa have failed prematurely over the last 20 years [International Water and Sanitation Centre 2009]. And although there are no recent statistics available for energy projects, an early review of cookstove programs estimated that only 10% of the programs started before 1980 were operational two years after startup [Joseph 1983]. These failures are commonly attributed to a lack of training, failure to understand the cultural constraints of the community, or failures to engage the community. However, failure is common even in development projects that start with community engagement and include user training. Taking an example of a household water supply project in Djenné, Mali, the program engaged community members and correctly assessed the health problems of poor water quality but failed to realize that improved water access would increase water use and create more waste than the traditional wastewater disposal systems could process [Alderlieste and Langeveld 2005]. With nowhere for the wastewater to be discharged, it collected in the streets and actually increased waterborne disease [CAHBA 1999]. These and other unanticipated consequences that lead to project failure often stem from a lack of understanding the dynamical relationships between human, environmental, and engineered systems. Anecdotal evidence suggests that rural energy projects face the same challenges.

One step in addressing these challenges is a structured engineering design process. At its core, the engineering design process is a process of questioning. Throughout the design process an engineer must answer questions to translate criteria and constraints into a realized product. In the developed world, the questions that drive engineering design are generally defined for many products and services. Conversely, the questions that drive engineering design for rural energy needs in developing countries are often not well established. As such, rural energy development initiatives commonly do not have the tools needed to design rural energy solutions, and similarly, often lack the data and metrics to compare energy options. The lack of tools and understanding is particularly evident during the initial phases of engineering design associated with problem definition. This critical design phase is often defined by assumptions rather than a clear understanding of energy systems dynamics.

Developing clean energy options for rural villages poses many unique challenges. Unlike urban areas, rural villages commonly lack basic infrastructure. Families survive on subsistence-level agriculture with little financial savings. Diseases such as malaria, tuberculosis, and water borne illnesses are daily burdens. These challenges are perhaps greatest in sub-Saharan Africa given that the region has the highest rate of death and disease in the world [World Health Organization 2009a]. The rural electrification rate is 12% and 90% of the population relies on biomass fuel for cooking [International Energy Agency 2010, World Bank 2011a]. Recognizing this, the United Nations Millennium Villages Project has been testing development strategies to meet the needs of rural villages in Africa [Sanchez 2007]. But this effort is not representative of development projects worldwide. Considering the history of rural development projects, little focus has been given to the needs in sub-Saharan Africa relative to other regions in the world. For example, of the estimated 828 million people who have access to improved cookstoves, only 34 million reside in sub-Saharan Africa [World Health Organization and United Nations Development Programme 2009]. Nearly half a billion people in sub-Saharan Africa still lack access to clean, safe, and affordable energy and energy technologies [International Energy Agency 2010]. Sustainable energy solutions must address many challenges common to isolated rural villages but must also account for the unique local dynamics of each village system.

1.1. Overview

The primary goal of this thesis is to understand energy system dynamics for one isolated rural agricultural village in sub-Saharan Africa. This includes acquiring local empirical data on energy supply and use, identifying the factors that are significant to explaining energy supply and use, and comparing energy options based on their expected impact on the village energy system. The study focuses on a single village because the literature review and preliminary field study data indicated that per capita energy use can vary significantly within a country, district, and even between nearby villages. Empirical data on all forms of energy supply and energy use is obtained from the study village. The human, technical, and environmental factors that influence village energy are identified and described using quantitative and narrative data. Energy options are compared using representative worldwide values, suggesting that the conclusions are generally applicable and can be used to select energy options in the short-term and to define research directions in the long-term. Chapter 2 discusses prior rural energy studies, theories in domestic fuel choice, rural energy options, and methods used to compare rural energy options. Chapters 3, 4, and 5 present thesis research in the form of three journal articles that examine energy system dynamics for the study village of 770 people in Mali.

Chapter 3 describes the overall dynamics of village energy supply and use over a one-year period. Quantitative data and qualitative data are used to form a narrative description of village energy supply and use. Energy sources include wood, charcoal, petroleum products, and electricity. Energy use is reported over the year for a broad range of domestic, artisan, transport, and public energy uses. Domestic wood use accounts for over 90% of village energy, a finding consistent to the few rural energy studies that examined all facets of village energy supply and use. Seasonal patterns in wood collection rates are quantified. Financial expenditures are delineated for all energy sources and all consumers. Electricity is the prime domestic energy expenditure. Results indicate that a comprehensive sustainable energy solution for the village will need to address six functions of energy—cooked meals, hot water, warmth, clean water, lighting, and power for small electronics.

Chapter 4 introduces methods and data from a multifactorial analysis of fuel use for domestic cookstove applications. New cooking tests are designed for gathering fuel consumption data on actual cookstove use in the home. Fuel consumption data are presented for six meal types and five non-meal cookstove applications. Multiple regression analysis is used to identify and quantity the factors that are significant to explaining cookstove fuel consumption. Cookstove type is found to be less significant than several other factors at explaining fuel consumption for cooking. The factors that are more significant are commonly missing in studies used to compare cookstoves. Further, this study provides multiple methods to design field studies to examine cooking energy use based on the desired accuracy and resources of the study. New cooking technologies and changes in cookstove usage characteristics are discussed as means to reduce fuelwood consumption.

Chapter 5 examines the costs and expected benefits of various energy options to meet domestic cooking needs accounting for three-quarters of all village energy use. Options considered include new types of cooking equipment such as improved stoves and solar water heaters and changes in cookstove use such as ignition methods and communal eating. Sixty programmatic options are created using various combinations of these energy options and compared using program cost and expected reduction in wood use. Figures of merit include annualized investment cost and reduction in fuelwood use, a proxy for assessing option impact on human health and the environment. Wood savings are evaluated in the ideal case of complete adoption and replacement, and then discounted using field data to form a more accurate picture of expected savings to aid in the design planning and design selection process. The high prevalence of stove stacking suggests a single cookstove could easily displace 20% to 80% less fuelwood than the rated design performance, and that multiple cooking technologies or solar water heaters may be needed to achieve substantial reductions in wood use. Chapter 6 summarizes the conclusions and presents opportunities for future research.

The primary researcher and author of the journal articles is Nathan G. Johnson, graduate student, advised by Kenneth M. Bryden, Associate Professor, Department of Mechanical Engineering, Iowa State University.

1.2. Summary

This thesis presents findings from a study of energy system dynamics for a single village in sub-Saharan Africa. Results are presented in three journal articles: (1) the overall dynamics of village energy supply and use for a one-year period, (2) the factors that influence fuel use for domestic cookstove applications, and (3) an assessment of the costs and benefits of various energy options for meeting domestic cooking needs. Mixed methods using quantitative and narrative data are used throughout to demonstrate how village energy supply and use are driven by dynamic human, natural, and engineered systems.

CHAPTER 2

BACKGROUND

2.1. Rural energy studies

Rural energy studies can be generally categorized by the type of energy source. Most studies of rural energy focus on the primary fuel, wood [AFVP 1989, Agostini et al. 1985, Arayal 1999, Assan 1991, Banks et al. 1996, Benjaminsen 1993, Bhatt and Sachan 2004a, Bhatt and Sachan 2004b, Bhatt et al. 1994, Bonnet-Madin, et al. 1983, CILSS 2006, Diombera 1993, Dukerley 1990, Eckholm 1975, Ensminger 1984, Ernst 1980, Food and Agriculture Organization 1983, Food and Agriculture Organization 1991, Food and Agriculture Organization 1992, Food and Agriculture Organization 1993, Food and Agriculture Organization 2002, Gill 1983, Hemstock and Hall 1995, Kersten et al. 1998, Kituyi et al. 2001, Leach 1988, Mangue 2000, Marufu et a. 1997, März 1986, Miah et al. 2009, Mulombwa 1998, Mung'ala and Openshaw 1984, Njiti and Kemcha 2002, Openshaw 1973, Osei 1993, Ramachandra et al. 2000, Reddy et al. 2000, Sarmah et al. 2002, Singh et al. 2010, Vermeulen et al. 2000, Wijesinghe 1984, Wood and Baldwin 1985]. Fewer studies examine multiple energy sources [Best 1979, Hemstock and Hall 1995, Hosier 1984, Hosier 1986, Kankam and Boon 2009, Kersten et al. 1998, Madubansi and Shackleton 2006, Marufu et al. 1997, Masera 1993, Ramachandra et al. 2000, Reddy 1982, Vermeulen et al. 2000].

Rural energy studies have been completed at regional, national, district, village, and household levels. The majority of this information is available from regional and national studies. Regional and national energy use statistics provide an easily accessible source of information. Organizations that collect national data include the International Energy Agency

(IEA), the Food and Agriculture Organization (FAO), the United Nations (UN), the World Resources Institute (WRI), and governmental departments around the world. The sources commonly report aggregate energy use at the national level. The advantage of national statistics is that they report the magnitude of energy use across a country. The disadvantage of national statistics is that it is difficult to disaggregate the national data to specific localities. Additionally, the statistics may aggregate several energy sources into a single category, and often leave out contextual data that can be useful to understand patterns in energy supply and use. For example, The World Health Organization (WHO) provides national data on the percentage of a people using solid fuels for cooking [World Health Organization 2011], but the data does not indicate the type of solid fuel, the quantity of fuel used, how the fuel was obtained, and other information related to energy supply and use that are critical to engineering energy solutions. Noting this trend in the lack of data on energy use, the United Nations Development Programme (UNDP) has stressed that "continued efforts are required to improve the quantity and quality of statistical information related to energy access," [2009].

2.1.1. Wood consumption

Rural energy studies have commonly focused on wood for its central role in domestic energy [Barnard 1987, de Montalembert and Clement 1983, Dunkerley et al. 1981, Howes 1985, Leach 1988, Wood and Baldwin 1985]. Additionally, these studies were motivated by the "wood fuel crisis" that became a popular hypothesis to describe energy use in developing countries around the same time as the world oil crisis in the 1970s [Anderson 1986, Eckholm 1975, Eckholm et al. 1984, Grainger 1982, Hosier 1988, Osei 1993]. The hypothesis suggested that growth in wood demand could not be supported by forest reserves, thereby creating wood scarcity, and consequently, reduced livelihood quality. A series of studies by the FAO has examined this issue and found that wood scarcity was not as severe as expected in much of sub-Saharan Africa [Food and Agriculture Organization 1983]. Similar studies in South and South-East Asia showed wood scarcity in only some countries [Food and Agriculture Organization 1992, Food and Agriculture Organization 1993, Food and Agriculture Organization 1997]. More recently, the FAO examined wood scarcity at the district level using wood supply density maps and population density maps in Rwanda [Food and Agriculture Organization 2011]. This study indicated that the extent of wood scarcity differed by district, and that in districts with high wood scarcity, agricultural residues were being used to supplement wood as fuel. The advantage of this methodology is that it provides a high resolution map of the balance between wood supply and wood demand. The disadvantage is that the wood consumption rates at the district-level are calculated from per capita consumption rates that have been averaged across many districts. These averaged values may poorly represent wood consumption dynamics at the local level.

Several studies have discussed the local factors that affect wood consumption [Best 1979, Bhatt and Sachan 2004a, Brouwer and Falcão 2004, Howes 1985, Kersten et al. 1998, Kituyi et al. 2001, Marufu et al. 1997, Miah et al. 2009, Ramachandra et al. 2000, Sarmah et al. 2002, Vermeulen et al. 2000]. Kituyi et al. completed a country-wide study of rural wood use in Kenya and reported per capita consumption rates that varied by approximately 340% [Kituyi et al. 2001]. Meal type, fuel scarcity, distance to source, and cost were discussed as factors affecting wood consumption. Studies focusing on villages and communities have also noted that ease of access affects wood consumption [Best 1979, Marufu et al. 1997, Sarmah et al. 2002]. In a study of four rural communities in Zimbabwe, Marufu et al. reported per capita wood consumption rates in the community with low deforestation to be a factor of 2.5 higher than a community with high deforestation [Marufu et al. 1997]. Another local factor that affects wood consumption rates is the regional climate or season [Best 1979, Bhatt and Sachan 2004a, Brouwer and Falcão 2004, Ramachandra et al. 2000, Sarmah et al. 2002]. A study by Bhatt and Sachan along a mountain range in India reported that wood consumption increased by a factor of two to three during winter [Bhatt and Sachan 2004a]. At the household level, differences in family sizes have been reported to affect per capita wood consumption rates [Kersten et al. 1998, Marufu et al. 1997, Miah et al. 2009, Vermeulen et al. 2000]. In a study of fuel and wood use in rural Zimbabwe, Vermeulen et al. noted that in the approximately 1500 households surveyed, per capita wood consumption decreased by a factor of four as family size increased from two to twelve people [Vermeulen et al. 2000].

Survey design can also influence findings in a wood consumption study, as suggested by Howes in a review of rural energy surveys [Howes 1985]. Howes noted that consumption rates of a single family can vary by a factor of two in consecutive days of a rural energy survey, and even more between seasons. Howes suggests that studies with single measurements of energy use or imprecisely phrased questions may not capture representative data or recognize trends in energy use. Additionally, Howes indicated that rural energy surveys have a difficult time recording single-fuel use for multiple end-uses, or when more than one fuel is used for a single end-use. This is a significant issue because it is difficult to explain the underlying causes or trends in energy use. Only a handful of studies report disaggregated energy use data for some applications [Bhatt and Sachan 2004b, Madubansi and Shackleton 2006, Masera 1993, Ramachandra et al. 2000, Reddy 1982, Sarmah et al.

2002, Sinha et al. 1998], and of those, few make the important distinction between wood consumption for cooking and water heating [Masera 1993, Ramachandra et al. 2000, Reddy 1982].

2.1.2. Village energy

In contrast with the number of studies on rural wood consumption, there are few published studies that focus on multiple energy sources [Best 1979, Hosier 1984, Hosier 1986, Kersten et al. 1998, Kituyi et al. 2001, Madubansi and Shackleton 2006, Marufu et al. 1997, Ramachandra et al. 2000, Reddy 1982, Sarmah et al. 2002, Vermeulen et al. 2000]. Several of these studies have been completed in India [Ramachandra et al. 2000, Reddy 1982, Sarmah et al. 2002]. Two notable studies in India examined multiple energy sources for domestic use [Ramachandra et al. 2000, Sinha et al. 1998]. Sinha et al. synthesized secondary data from many studies completed on domestic energy use for 638 villages across 14 of 15 agro-climatic regions in India [Sinha et al. 1998]. The dataset was sparse, but some general conclusions were extracted. Wood contributed to 58% of energy used for cooking with dung and agricultural wasted contributing equally to the remaining share. Kerosene provided a minor share of energy used for cooking, but was the primary contributor to energy used for lighting, followed by electricity. Ramachandra et al. confirmed much of these earlier findings in a survey of 90 villages to study regional and seasonal effects on energy use [Ramachandra et al. 2000]. The study indicated that households in villages with good wood access used less kerosene. Additionally, the study noted that approximately 98% of households used traditional wood fires for cooking and water heating. No data was discussed for space heating.

Two additional studies in India focused on all village energy use [Reddy 1982, Sarmah et al. 2002]. Reddy completed an energy-use census of six Indian villages and reported energy utilization for domestic (88.3%), agriculture (4.7%), lighting (2.2%), transport (0.5%), and industry (4.7%) applications [Reddy 1982]. Energy sources included wood (81.6%), human energy (7.7%), animal energy (2.7%), kerosene (2.1%), electricity (0.6%), and other sources (5.3%) that include rice husks, agricultural wastes, coal, and diesel. Per capita energy use for each village ranged from 10,800 to 13,900 MJ cap^{-1} yr^{-1}. A similar study in the Indian state Assam by Sarmah et al. reported per capita energy use for six rural villages at 7,500 to 12,700 MJ cap^{-1} yr^{-1} [Sarmah et al. 2002]. This study reported that agriculture wastes and dung were not used as fuel due to the high availability of wood.

Several studies have been completed of domestic energy use in sub-Saharan Africa [Arrayal 1999, Best 1979, Hosier 1984, Hosier 1986, Kersten et al. 1998, Kituyi et al. 2001, Madubansi and Shackleton 2006, Marufu et al. 1997, Vermeulen et al. 2000]. Best measured domestic use of dung, kerosene, and wood in three villages in South Africa, taking data at three time periods in one year for each village [Best 1979]. The study estimated annual energy use rates of 7,700, 10,300, and 23,900 MJ cap^{-1} yr^{-1} for domestic applications. The greater amount of energy use in the last village was attributed to ease of wood access. The village with the good wood access did not use dung as fuel whereas a village with poor wood access used dung for up to 52% of energy needs. More recently, a study in South Africa examined changes in energy use patterns following electrification in five rural villages using a longitudinal study over a ten-year period [Madubansi and Shackleton 2006]. Field research showed that the use of electricity depended strongly on the end-use application. The study found that grid electricity had (1) displaced the majority of dry-cell battery use for personal electronics, (2) almost completely displaced the use of candles and kerosene for lighting, and (3) had little effect on the use of wood and kerosene for cooking and heating. This indicates that electricity did not completely replace the use of other energy sources, but that electricity was adopted as an additional energy source suited to certain applications.

2.2. Domestic fuel choice

The study by Madubansi and Shackleton indicates a defining trend in rural domestic energy use known as "fuel stacking". This describes the trend in which consumers use multiple fuels without displacing the use of traditional fuels, thereby stacking or adding additional energy sources to their current energy options [Brouwer and Falcão 2004, Hiemstra-van der Horst and Hovorka 2008, Joon et al. 2009, Madubansi and Shackleton 2006, Masera et al. 2000, Troncoso et al. 2007, Vermeulen et al. 2000]. This is counter to urban energy use studies that often describe the household energy transition as an "energy ladder" in which households gradually progress away from low-quality fuels such as biomass to higher-quality fuels such as electricity and LPG [Leach 1988, Hosier 2004]. Studies supporting the "energy ladder" hypothesis suggest that factors such as income [Campbell et al. 2003, Davis 1998, Hosier and Dowd 1987], the unit cost of fuel [Leach 1988], the extent of urbanization in the community [Pachauri and Jiang 2008], and the electrification rate in the community can in part explain the household energy transition towards modernized fuels [Davis 1998, Heltberg 2004]. In review of these studies, Hiemstra-van der Horst and Hovorka noted that the only commonality between the differing perspectives is that high fuel prices relative to income often prevent the poor from using modernized fuels [Hiemstra-van der Horst and Hovorka 2008]. Another viewpoint of household energy transition suggests that consumers may "leapfrog" from wood to electricity, skipping over charcoal and kerosene in their transition [Murphy 2001].

A detailed study examining the change in rural energy use practices was completed by Davis in South Africa [Davis 1998]. His study examined the effects of access to electricity on fuel choice. Although he states there is evidence of an energy transition in rural households, his findings also contrast the extent of this transition in that

> "It is clear that the majority of households utilise a number of different fuels. In many cases different fuels are selected for different end-uses, and it is also common for a household to use two or more fuels for one application (especially cooking)" [Davis 1998].

Davis goes onto say that

> "For a larger proportion of electrified households, particularly those in the low and medium income groups, electricity appears to act as an additional fuel, rather than a replacement for other fuels. This is shown clearly in the tendency for electrified households to use four or more fuels (29%), compared with unelectrified households (6%)" [Davis 1998].

Davis reports that the greatest evidence of a transition away from solid fuels towards conventional fuels occurs in high income electrified homes. Further, the study notes that electrified households spent more money on energy, regardless of income level.

Several studies have supported the finding from Davis that households with multiple fuels commonly use more than one end-use technology, often for cooking [Hiemstra-van der Horst and Hovorka 2008, Joon et al. 2009, Kersten et al. 1998, Masera and Navia 1997, Masera et al. 2000, Pine et al. 2011, Ruiz-Mercado et al. 2011]. Two articles discuss this behavior in detail for the Patsari cookstove program in southern Mexico [Pine et al. 2011, Ruiz-Mercado et al. 2011]. Ruiz-Mercado et al. report that just over half of Patsari owners used the stove for most cooking needs, while other cooking tasks were completed using a traditional cooking fire, LPG, or a microwave [Ruiz-Mercado et al. 2011]. Pine et al. reported that cookstoves were used interchangeably for many tasks, indicating the importance to understand the variety of tasks completed with the cookstove in addition to the rate of use in estimating cookstove impact [Pine et al. 2011]. Interestingly, even in households with a single energy source there can be multiple types of cookstoves, generally wood cookstoves [Miah et al. 2009]. This can be attributed to each cookstove suited to a specific application, or a cookstove fixed in a single location when it is desired to cook elsewhere (e.g. cookstove is fixed indoors but high seasonal temperatures move people outdoors to cook).

2.3. Rural energy options

Rural energy needs in developing countries are numerous. Reddy et al. 2000 reviewed many of these needs and corresponding rural energy projects to develop a list of technical options for rural energy (Table 1) [Reddy et al. 2000]. Reddy et al. categorized these options into near-, medium-, and long-term options that offer a pathway to immediate improvement and a continuous flow of improved technologies:

- Near term (in the next 5 years): alternatives that offer a potential for immediate improvement;
- Medium term (5–15 years): technologies that can provide dramatic improvements;
- Long term (15–30 years): technologies with benefits of medium term options that are also consistent with sustainable development goals.

Table 2.1. Technology options for rural energy needs.[a]

Energy source/task	Present	Near term	Medium term	Long term
Electricity	Grid or no electricity	Natural gas combined cycles, biomass-based generation using gasifiers coupled to internal combustion engines, photovoltaic, small wind, small hydroelectric for applications remote from grids	Biomass-based generation using gasifiers coupled to microturbines and integrated gasifier combined cycles, mini grids involving various combinations of photovoltaic, wind, small hydroelectric, batteries	Grid-connected photovoltaic and solar thermal, biomass based generation using gasifiers coupled to fuel cells and fuel cell/turbine hybrids
Fuel	Wood, charcoal, dung, crop residues	Natural gas, LPG, producer gas, biogas	Syngas, dimethyl ether	Biomass-derived dimethyl ether with electricity coproduct
Cogeneration (combined heat and power)		Internal combustion engines, turbines	Microturbines and integrated gasifier combined cycles	Fuel cells, fuel cell/turbine hybrids
Cooking	Woodstoves	Improved woodstoves, LPG stoves, biogas	Producer gas, natural gas, and dimethyl ether stoves	Electric stoves, catalytic burners
Lighting	Oil and kerosene lamps	Electric lights	Fluorescent and compact fluorescent lamps	Improved fluorescent and compact fluorescent lamps
Motive power	Human- and animal-powered devices	Internal combustion engines, electric motors	Biofueled prime movers, improved motors	Fuel cells
Process heat	Wood, biomass	Electric furnaces, cogeneration, producer gas, natural gas/solar thermal furnaces	Induction furnaces, biomass/solar thermal furnaces	Solar thermal furnaces with heat storage

[a]Adapted from Reddy et al. 2000.

Some options that deserve further attention are cookstoves, solar lighting, solar heating, and micro-grid power.

2.3.1. Cookstoves

Biomass cookstoves are in common use throughout the developing world. Biomass cookstoves are responsible for respiratory illness and death [Desai et al. 2004], disease and morbidity from collecting wood over long distances [Wickramasinghe 2003], and burns, cuts, and scalds from using traditional three-stone fires and small hand-crafted cookstoves [Johnson 2005]. The World Health Organization estimates that 2 million people die each year from cooking with solid fuels on indoor cookstoves [World Health Organization 2009b]. This is primarily women and children who spend several hours per day in close proximity to the cooking fire [Bruce et al. 2000]. Outside of the home, cookstoves have been implicated in deforestation and regional climate change [Bond and Sun 2005, Manibog 1984, Ramanathan and Carmichael 2008].

Efforts to reduce the impact of traditional biomass cookstoves are not new. To date, improved cookstoves have been distributed to 830 million of the three billion people using solid fuels for cooking in developing countries [World Health Organization and United Nations Development Programme 2009]. However, early programs between 1950 and 1980 had little success, with an estimated 90% of programs failing within two years [Joseph 1983]. These failures have been attributed to a lack of cookstove testing, poor quality control, lack of consumer research, and poor program monitoring [Gill 1987, Joseph 1983, World Bank 2011b]. Although the potential of improved cookstoves to reduce fuel consumption and emissions has been shown in laboratory and field tests [Adkins 2010a, Boy 2000, Jetter and Kariher 2009, MacCarty 2010, Smith et al. 2007], no methodology has been selected as the global standard to compare cookstoves from a review of current methods in use [Adkins

2010a, Bailis et al 2007, Boy 2000, Doroski and Jetter 2011, Granderson et al. 2009, Johnson et al. 2010, World Health Organization 2008].

Examples of improved cookstoves are shown in Fig. 1 [Doroski and Jetter 2011]. Most cookstove types use wood for fuel, though others use charcoal, pellets, rice hulls, corn cobs, and plant oil. The cookstoves in Fig. 1 were collected from Central and South America, Africa, and Asia for use in laboratory tests of emissions and performance. In multiple tests comparing performance, the study reported the thermal efficiency of a three-stone fire was 13% to 15%, improved natural draft wood cookstoves fell between 11% and 53%, improved forced draft wood cookstoves were between 9% and 43%, and charcoal cookstoves were between 14% and 37%. This demonstrates that an improved cookstove may not have better efficiency than a three-stone fire, and as such, may use more fuel to complete a cooking task. A similar study comparing 50 cookstoves using laboratory tests reported that the improved natural draft wood cookstoves with a “rocket” combustion chamber recued fuel use by 33%, CO emissions by 75%, and particulate matter (PM) emissions by 46%, on average, compared to a traditional wood three-stone fire [MacCarty et al. 2010]. Additional findings reported that forced draft wood cookstoves reduced fuel use by 40% and emissions by 90% compared to a traditional three-stone fire. Traditional charcoal cookstoves used a similar amount of energy in the water boiling test to that of wood three-stone fires, increased CO emissions by a factor of two, and decreased PM emissions by 80%. Charcoal cookstoves with the “rocket” combustion chamber reduced energy use by one-third and decreased emissions by one-half compared to traditional charcoal cookstoves. Improved cookstoves can be as low as US$5 for artisan-made wood cookstoves or as high as US$300 for complete biogas systems [World Bank 2011b].

A. Ceramic Jiko, charcoal
B. Metal Jiko, charcoal
C. Belonio, rice hull
D. Onil, wood
E. Protos, plant oil
F. Mayon Turbo, rice hull
G. Oorja, pellet
H. KCJ, charcoal
I. GERES, charcoal
J. StoveTec, charcoal
K. Jinqilin CKQ-80I, cobs
L. 3-Stone Fire, wood
M. Upesi, wood
N. Uhai, charcoal
O. Gyapa, charcoal
P. Envirofit G-3300, wood
Q. Sampada, wood
R. Berkeley Darfur, wood
S. StoveTec TLUD, pellet
T. Philips HD4012, wood
U. Philips HD4008, wood
V. StoveTec, wood

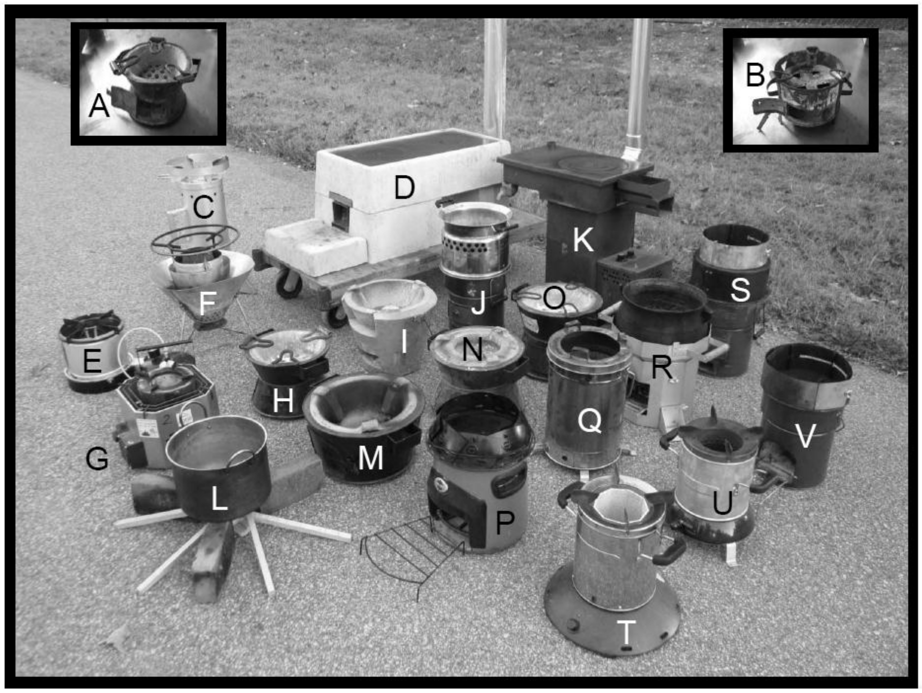

Figure 2.1. Assortment of improved cookstoves [Doroski and Jetter 2011].

2.3.2. Solar water heating

Water heating has been noted as a significant contributor to domestic wood consumption in the few studies that differentiate energy use by end-use application [Masera 1993, Ramachandra et al. 2000, Reddy 1982]. The improved cookstoves discussed earlier offer one option to reduce wood consumption for water heating. Solar water heaters are an additional energy option. Solar water heaters can completely displace the use of wood or other consumable fuels in heating water for bathing, washing, and other household needs. Low-cost portable solar water heaters have been introduced in South Africa as shown in Fig. 2. The wheel barrow and soft tank shower have capacities of 30 liters and 18 liters and cost US$120 and US$10, respectively [Manyaapelo 2000]. Low-cost fixed units with a larger capacity of 100 liters have been researched to provide hot water between 50°C to 60°C at a cost of US$160 (using exchange rate US$ 1 = 50 Indian Rupees) [Nahar 2002]. The flat-panel collector in the study used alternative materials to reduce cost by replacing conventional copper components with galvanized steel and aluminum.

Figure 2.2. Low-cost portable solar water heaters: (a) wheel barrow type, (b) soft tank shower [Manyaapelo 2000].

2.3.3. Solar lighting

Several studies have examined the use of solar photovoltaics (PV) as a power source for household lighting [Adkins et al. 2010c, Jones et al. 2005, Mahapatra et al. 2009, Mills 2003, Mukerjee 2007, Nouni et al. 2006, Rubab and Kandpal 1996, Sebitosi and Pillay 2007]. Solar PV lighting is a common off-grid alternative to fuel-based lighting such as burning wood, candles, kerosene, oils, and gaseous fuels. It can also be used as a supplementary power source for homes connected to the electric grid. Solar power systems can be centralized in a village as an array of solar PV panels, decentralized at households with one panel per home, or integrated panel-lighting systems such as a hand-held solar lantern.

Development projects using solar PV commonly power compact fluorescent lights (CFLs) and light-emitting diodes (LEDs) due to the low power requirements and longer life of these light sources compared to incandescent bulbs [Adkins et al. 2010c, Jones et al. 2005, Mahapatra et al. 2009, Mills 2003]. A study comparing multiple fuel-based, grid-connected, and off-grid lighting options reported that PV systems with a battery and LEDs had the lowest cost of ownership (fixed and variable costs) [Mills 2003]. However, the comparative benefit of PV and LED systems depends on local fuel prices which the study observed between US$0.10 to US$2.00 per liter of kerosene.

2.3.4. Micro-grid power

Approximately one-fifth of the world's population lacks access to electricity, and over 80% of the people lacking a grid connection live in rural households [International Energy Agency 2010]. Micro-grid power is one solution for remote areas where the cost of expanding the utility electric grid is high. These solutions are generally referred to as "island" solutions because they are isolated from contact with the electric grid. Micro-grid power systems are placed at consumer sites, and generally have high reliability, low voltage, and low emissions [Lasetter 2002]. Multiple energy sources can be coupled with storage devices and controlled loads in advanced systems [Venkataramanan and Marnay 2008].

Micro-grid power systems that couple renewable and conventional energy sources have shown potential in providing an alternative to grid electricity in remote areas of developing countries [Agalgaonkar et al. 2006, Flowers et al. 2000, Gupta et al. 2010, Mitra et al. 2008, Rogers et al. 2007]. A notable program by the National Renewable Energy Laboratory (NREL) has installed several hybrid renewable power systems in rural villages since 1994. From these experiences, NREL's Renewables for Sustainable Village Power drafted a report discussing projects and summarizing lessons learned [Flowers and Baring-

Gould 2004]. Many of these lessons focused on the financial, political, technical, and programmatic criteria for sustainability. The authors suggested that an integrated approach of the aforementioned criteria was needed for project sustainability. Additionally, the report indicated that "there is no universal best delivery model for rural energy services; the optimal approach requires matching the needs and capabilities of both the users and the service providers" [Flowers et al. 2000].

2.4. Comparing energy options

Methodology is needed to compare energy options because there is no universal solution to rural energy needs. First, need is local. Villages in colder climates may require space heating while villages in warmer climates may need electricity for lighting or to power pumps to access clean water. Second, the quality of the energy source is local. One region can be suitable for wind power yet is unsuitable for solar PV. Hydroelectric generators can be appropriate in villages near rivers where other energy options are infeasible. Third, consumer requirements are local. Preferences can differ between consumer groups, and further define the solution space, possibly requiring multiple solutions to meet a single need. Lastly, local policies, financing mechanisms, technology, infrastructure, and human capacities affect the sustainability of any rural energy option as previously suggested in [Flowers et al. 2004]. Examining these factors and comparing the costs and benefits of rural energy options has been the subject of many studies [Asif and Muneer 2006, Bruce et al. 2011, Buchholz and Da Silva 2010, Claude Davis & Associates 2010, Erickson et al. 2009, García-Frapolli et al. 2010, Gupta et al. 2010, Nahar 2002, Partnership for Clean Indoor Air 2011, Pokharel 2004, Pohkarel and Chandrashekar 1998, Practical Action 2010, Reddy and Subramanian 1979, Reddy et al. 2000, Shaahid et al. 2004, Spalding-Fecher et al. 2002, Tewari and Srinath 1979, Winrock International 2004].

2.4.1. Energy planning

Several studies have reviewed the history of energy options and offered pathways for energy option development [Bruce et al. 2011, Practical Action 2010, Reddy et al. 2000, Winrock International 2004]. In a review of household energy interventions and policies over the last 30 years, Bruce et al. report that improved cookstoves have yielded the most cost-effective benefit compared to other options [Bruce et al. 2011]. The authors go onto state that the success of energy options will depend on the coordinated effort of governments, businesses, non-governmental organizations (NGOs), and community groups. A similar study by Reddy et al. proposed short-, medium-, and long-term technical options for energy supply and energy use [Reddy et al. 2000]. Supporting this outline for technical development, the authors state that new development strategies, financial mechanisms to cover initial costs, integration with other policies, and the involvement of local consumers are needed to improve the success of energy projects. A report by Practical Action examined the energy needs and access to basic energy services of poor people in developing countries [Practical Action 2010]. After reviewing historical data and case studies of energy projects, the report states that a combined approach that considers policy, financing, and capabilities is needed to enable access to basic energy services. In all studies the principal focus is on cookstoves and lighting or electrification second. And while these studies suggest potential pathways in rural energy development, there is still research needed in comparing options to determine the most sustainable and beneficial direction along any chosen pathway. A study by Winrock

International answers some of these questions by identifying the small-scale power systems that can meet the energy requirements of information and communication technologies in rural energy projects [Winrock International 2004].

2.4.2. Feasibility and costing

Studies of energy option feasibility, including financial analysis, are common [Buchholz and Da Silva 2010, Claude Davis & Associates 2010, Erickson et al. 2009, Gupta et al. 2010, Pohkarel and Chandrashekar 1998, Reddy and Subramanian 1979, Shaahid et al. 2004, Spalding-Fecher et al. 2002, Tewari and Srinath 1979]. Two notable studies comparing rural energy options were completed in India [Reddy and Subramanian 1979, Tewari and Srinath 1979]. Reddy and Subramanian compared energy options for a rural village using methodology to understand current energy use patterns, define energy needs, consider technically feasible solutions, and select options to meet each need [Reddy and Subramanian 1979]. A biogas digester was proposed to meet multiple needs for the village while relying upon local energy sources and minimizing wasted energy compare to other options. At the time of the study there were little quantitative data available for comparing technologies, and the authors relied primarily on heuristics for selecting the energy option. Another study in India focused on a single energy need and compared options using utility functions [Tewari and Srinath 1979]. Utility functions were defined for eight metrics of appropriateness that included capital cost, reoccurring cost, social acceptance, use of local materials, and other metrics. Each utility function was multiplied by a corresponding importance weight and summed to compute an overall utility for each energy option. The advantage of this method is that options can be compared using a single metric, the disadvantage is that the definition of utility curves and importance weights will likely differ between stakeholders, and the data aggregation may not represent an optimal solution for all stakeholders. The disadvantage of an aggregated preference metric can be extracted from studies finding that not all consumers adopt a new technology [Ruiz-Mercado et al. 2011]. These studies indicated further nuances in stakeholder preference when women used cookstove options at different rates for different end needs.

Similar issues can arise in cost-benefit analysis (CBA) when aggregating financial valuations of costs and benefits associated to each option. An aggregate cost-benefit ratio may not adequately represent the detail needed for comparing energy options when objectives differ between policy makers and consumers. Additionally, financial valuation of consumer's time can be difficult or nonsensical in rural villages where no wage earning opportunities are available. These difficulties have been noted by a recent study, "economic evaluation is at an early stage, and there is need for more empirical evidence on costs and the full range of benefits associated with various interventions across a range of settings" [Bruce et al. 2011].

The levelized cost of energy is another metric used to compare options during feasibility and financial analysis. This expresses the net present cost per unit energy for the lifetime of the energy option. It is commonly used in comparing options for electric service in developed countries [Energy Information Administration 2011], and has been extended to applications in developing countries [Buchholz and Da Silva 2010]. A notable study by Buchholz and Da Silva compared four electrification alternatives for rural Uganda using capital cost and electricity production cost to determine the preferable option with the lowest cost, but did not include consideration of carbon emissions in their analysis. Levelized cost can be used for selecting the option with lowest cost per unit energy, but commonly does not consider other factors that affect sustainability such as social acceptability, ease of programmatic or technical management, resource availability, and financing mechanisms. Additionally, levelized cost makes an implicit assumption that costs can be spread over the lifecycle of the energy option. Although this is a reasonable assumption in developed countries with access to loans that spread large expenditures over many years, the assumption poorly describes financial mechanisms in rural villages that often lack loans. When confronted with a lack of liquid capital, villages are often unable to pay lump-sum costs for operation and maintenance, thereby leading to failure of the installed energy option.

2.4.3. Empirical evaluation

Empirical studies of energy options are also common [Asif and Muneer 2006, García-Frapolli et al. 2010, Partnership for Clean Indoor Air 2011, Pokharel 2004, Nahar 2002]. In a study of solar water heaters in Pakistan, Asif and Muneer compared options using a lifecycle assessment of capital cost and carbon savings [Asif and Muneer 2006]. The payback period of each energy investment was calculated from the capital cost and carbon credit value. A study by Pokharel used field data and laboratory data to calculate the levelized cost of energy options for cooking [Pokharel 2004]. One influential finding was that the choice of a cooking utensil influenced the amount of energy needed to complete a task, and consequently, affected the levelized cost of energy, indicating that local consumer choices can affect option cost-benefit ratios. In a study valuing the economic impacts of a cookstove intervention in Mexico, García-Frapolli et al. reported that improved cookstoves had a high benefit/cost ratio of between 11.4:1 and 9:1 [García-Frapolli et al. 2010], a finding supported by a review article of multiple energy options discussed earlier [Bruce et al. 2011]. The study found that the largest economic benefits from the cookstove intervention came from the reduction in wood use and health impacts.

2.5. Summary

Understanding village energy supply and use is a fundamental step in designing and selecting rural energy options. This requires (1) local empirical data on energy supply and use that is commonly not available, or if available, lacks the detail needed to understand village energy system dynamics and compare energy options, (2) identification of the human, natural, and engineered system factors that influence energy flow in the village, and (3) a methodology and metrics to compare the costs and benefits of energy options for all involved stakeholders. This thesis addresses these research areas during the study of a single village in West Africa.

CHAPTER 3

ENERGY SUPPLY AND USE IN A RURAL WEST AFRICAN VILLAGE

Submitted draft of a paper accepted for publication in *Energy*

Nathan G. Johnson, Kenneth M. Bryden

Abstract

Over three billion people live in the rural areas of low- and middle-income countries. Often rural households have many unmet energy needs, including cooking, lighting, heating, transportation, and telecommunication. Designing solutions to meet these needs requires an understanding of the human, natural, and engineered systems that drive village energy dynamics. This paper presents the results of a novel study of energy supply and use over a one-year period in an isolated rural village of 770 people in Mali. Quantitative data and narrative descriptions from this study portray village energy supply and use. Annual village energy use is 6,000 MJ cap^{-1} yr^{-1}. Domestic energy needs account for 93% of village energy use. Wood is the primary energy source and provides 94% of the village energy supply. Approximately 98% of the wood is used for domestic consumption. The uses of wood in the home are cooking (52.2%), heating water (22.2%), space heating (19.1%), and other activities (6.5%). This paper also reports variations in energy usage over the period of a year for a broad range of domestic, artisan, transport, and public energy uses.

Key words

Village energy, wood consumption, sustainability, rural Africa, Sahel, developing country

3.1. Introduction

Over three billion people live in rural areas of low- and middle-income countries [World Bank 2008]. Rural households often have many unmet energy needs, including cooking, lighting, heating, transportation, and telecommunication. Rural households account for 85% of the 1.4 billion people lacking access to electricity worldwide, and they account for 83% of the 2.7 billion people who rely on biomass fuels for cooking worldwide [International Energy Agency 2010]. Because of this, rural energy development is a critical global need that can save time, improve health, and help to preserve the environment [Bond and Sun 2005, Jetter and Kariher 2009, Madubansi and Shackleton 2006, Ramanathan and Carmichael 2008]. However, realizing these benefits in rural villages poses unique challenges.

Development project failure is common. For example, approximately 50,000 rural water points in Africa are broken [Skinner 2009], and an estimated 30% of all water projects in sub-Saharan Africa have prematurely failed in the last 20 years [International Water and Sanitation Centre 2009]. Although there are no recent statistics available for energy projects, an early review of cookstove programs estimated that only 10% of the programs before 1980 were operational two years after startup [Joseph 1983]. In addition, anecdotal evidence suggests that energy projects developed for rural villages have a mixed record of success similar to that of water projects.

This paper presents the results of a field study of energy supply and use over the period of a year in an isolated rural agricultural village of 770 people in Mali. Quantitative data and narrative descriptions from this study portray energy supply and use in this rural sub-Saharan village. All methods and data discussed in this paper were approved by the Institutional Review Board at Iowa State University.

3.2. Background

Designing locally sustainable energy solutions for isolated rural villages requires a detailed understanding of the dynamics of energy supply and use within the village. However, there have been few studies that have focused on the dynamics of rural energy use. Recognizing this, the United Nations Development Programme (UNDP) has stated "continued efforts are required to improve the quantity and quality of statistical information related to energy access," [Legros et al. 2009]. In general, rural energy studies can be divided into two types—those that focus on the primary fuel, wood, and those that focus on multiple energy sources.

There are a large number of studies addressing rural wood consumption [AFVP 1989, Agostini et al. 1985, Assan 1991, Banks et al. 1996, Benjaminsen 1993, Bhatt and Sachan 2004a, Bhatt and Sachan 2004b, Bhatt et al. 1994, Bonnet-Madin et al. 1983, Brouwer and Falcão 2004, Diombera 1993, Dukerley et al. 1990, Eckholm 1975, Ensminger 1984, Ernst 1980, Food and Agriculture Organization 1983, Food and Agriculture Organization 1991, Food and Agriculture Organization 1993, Food and Agriculture Organization 2002, Gill 1983, Hemstock and Hall 1995, Kituyi et al. 2001, Leach 1988, Mangue 2000, März 1986, Miah 2009, Ministry of Forestry Vietnam 1992, Mulombwa 1998, Mung'ala and Openshaw 1984, Njiti and Kemcha 2002, Openshaw 1973, Osei 1993, Reddy et al. 2000, Singh et al. 2010, Tangare 2006, Wijesinghe 1984, Wood and Baldwin 1985]. A pair of notable studies from India differentiates wood consumption for all domestic applications, and examines regional climate effects on energy use between lowland and highland villages in a mountainous area [Bhatt and Sachan 2004a, Bhatt and Sachan 2004b]. They found that cooking meals accounted for approximately one-half of wood consumption [Bhatt and Sachan 2004b], and that wood consumption increased by two- to three-fold during winter [Bhatt and Sachan 2004a]. In addition to the studies on rural wood consumption, there are several studies that examine multiple energy sources in rural villages [Arayal 1999, Best 1979, Hosier 1984, Hosier 1986, Kersten et al. 1998, Madubansi and Shackleton 2006, Marufu et al. 1997, Ramachandra et al. 2000, Reddy 1982, Sarmah et al. 2002, Vermeulen et al. 2000]. Two studies in the Indian state Karnataka looked at wood consumption in similar detail and expanded the analysis to include multiple energy sources [Ramachandra et al. 2000, Reddy 1982]. Ramachandra et al. performed a broad survey of 90 villages to study the regional and seasonal effects on energy use, but did not include space heating [Ramachandra et al. 2000]. Reddy performed a comprehensive study measuring all energy use in six villages. Per capita energy use for each village ranged from 10,800 to 13,900 MJ cap^{-1} yr^{-1} [Reddy 1982]. Village energy utilization sectors were domestic (88.3%), industry (4.7%), agriculture (4.3%), lighting (2.2%), and transport (0.5%). A similar study in the Indian state Assam by Sarmah et al. reported that per capita energy use for six rural villages was 7,500 to 12,700 MJ cap^{-1} yr^{-1} [Sarmah et al. 2002]. This study reported that agriculture wastes and dung were not used as fuel due to the high availability of wood. In each study, wood was the primary energy source, and the primary end-use applications were domestic.

In sub-Saharan Africa there have been several studies of rural wood consumption [AFVP 1989, Agostini et al. 1985, Assan 1991, Banks et al. 1996, Benjaminsen 1993, Bonnet-Madin et al. 1983, Diombera 1993, Ensminger 1984, Ernst 1980, Gill 1983, Hemstock and Hall 1995, Kituyi et al. 2001, Mangue 2000, März 1986, Mulombwa 1998, Mung'ala and Openshaw 1984, Njiti and Kemcha 2002, Openshaw 1973, Tangare 2006]. Njiti and Kemcha reviewed the energy studies of Cameroon and found wood consumption rates were reported to be between 260 and 580 kg cap^{-1} yr^{-1} [Njiti and Kemcha 2002]. Their review also noted that most wood collection occurs during the dry season when there is no farming activity. In Mali, a recent study reported wood consumption in different districts, with 510 to 910 kg cap^{-1} yr^{-1} in the Sahel and 110 to 290 kg cap^{-1} yr^{-1} in the Niger delta and Sahara [Tangare 2006]. As shown in Fig. 3.1, rural domestic wood consumption varies in sub-Saharan Africa by a factor of approximately 15, from 110 to 1630 kg cap^{-1} yr^{-1}. Various studies have suggested that differences in wood consumption can be attributed to ease of wood access [Sarmah et al. 2002, Marufu et al. 1997, Best 1979], seasonal variations [Bhatt and Sachan 2004a, Brouwer and Falcão 2004, Ramachandra et al. 2000, Sarmah et al. 2002], differences in family size [Best 1979, Hosier 1984, Hosier 1986, Kersten et al. 1998, Marufu et al. 1997, Miah 2009, Vermeulen et al. 2000], or survey techniques [Howes 1985].

There are fewer studies that address multiple energy sources in sub-Saharan Africa [Arayal 1999, Best 1979, Hosier 1984, Hosier 1986, Kersten et al. 1998, Madubansi and Shackleton 2006, Marufu et al. 1997, Vermeulen et al. 2000]. Best measured domestic use of dung, kerosene, and wood in three villages in South Africa, taking data at three time periods in one year for each village [Best 1979]. The study reported annual energy use rates of 7,700, 10,300, and 23,900 MJ cap^{-1} yr^{-1}. The greater amount of energy use in the last village was attributed to ease of wood access. The village with an abundant wood supply used no dung. In contrast, one village with poor wood access used dung for one-third of its annual energy needs, and approximately one-half of its winter energy needs.

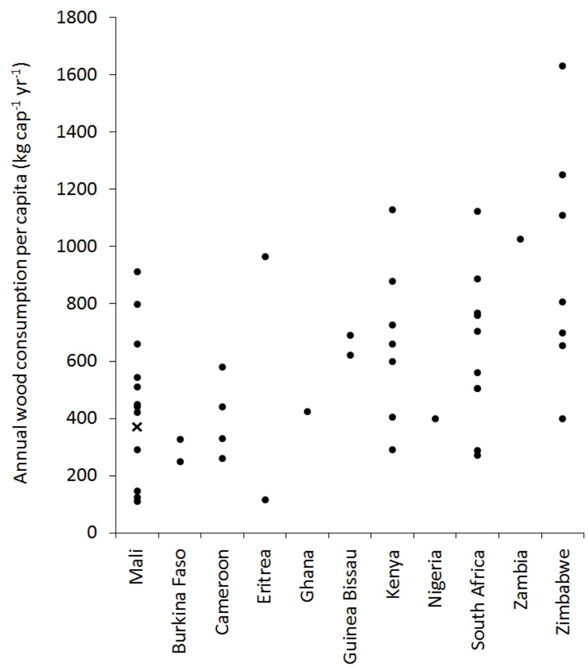

Figure 3.1. Domestic wood consumption in kg per capita per year for rural energy studies in sub-Saharan Africa. This study is indicated by an X. *Source:* Mali [Benjaminsen 1993, Bonnet-Madin et al. 1983, Tangare 2006], Burkina Faso [März 1986], Cameroon [AFVP 1989, Agostini et al. 1985, Assan 1991, Njiti and Kemcha 2002], Eritrea [Arayal 1999], Ghana [Osei 1993], Guinea Bissau [Diombera 1993], Kenya [Ensminger 1984, Hosier 1984, Kituyi et al. 2001, Mung'ala and Openshaw 1984], Nigeria [Kersten et al. 1998], South Africa [Banks et al. 1996, Best 1979, Madubansi and Shackleton 2006], Zambia [Mulombwa 1998], Zimbabwe [Hemstock and Hall 1995, Hosier 1986, Marufu et al. 1997, Vermeulen et al. 2000].

Madubansi and Shackleton performed a ten-year study of five villages in South Africa before and after grid electrification [Madubansi and Shackleton 2006]. Before grid electrification, domestic energy use for the five villages was 8,100 to 14,000 MJ cap^{-1} yr^{-1}. Households in the study used an average of four different energy sources before and after grid electrification. For heating and cooking, the study noted that 45% of households used only wood and 50% of households used wood and kerosene before grid electrification. Following grid electrification, the number of households using only wood remained unchanged; 22% of households used wood and kerosene, and 31% of households supplemented these fuels with electricity. Household fuel choice for lighting showed little evidence that electricity had replaced other options (8%), but it was common to find households that coupled electricity with candles and kerosene (76%). Before grid electrification, disposable batteries were used to power personal electronics in 81% of households. After grid electrification, only 28% of households used batteries.

3.3. Methodology

This study examines the dynamics of seasonal energy supply and use in a rural agricultural village in southern Mali. Four visits to the village were made as a part of this study. The initial visit in May 2009 was used to plan the study, followed by three field studies of four weeks each to conduct surveys and measurements in May, August, and December of 2010. These times were chosen to study seasonal variations in energy supply and use.

3.3.1. Study location

The village examined in this study is located in southern Mali within the Sahel. 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 to May); rainy and humid with moderate temperatures (June to October); and cool and dry (November to January).

Mali ranks 160th out of 169 countries on the Human Development Index, an index that accounts for life expectancy, educational attainment, and income [Klugman 2010]. Two-thirds of Mali’s 13 million people live in rural areas [World Bank 2008]. Mali has the sixth highest rate of death in the world due to indoor and outdoor air and water pollution [Klugman

2010]. The per capita energy use of 7,500 MJ cap^{-1} yr^{-1} is one-third of the average per capita energy use in Africa. On a national level, the mix of energy sources is biomass (78%), petroleum products (18%), and electricity (4%). Energy use is residential (72%), transport (17%), industrial (3%), and other applications (8%) [SIE-Mali 2007].

The village in this study has sixty families with a total population of 770 people. Every family lives on subsistence agriculture, and approximately 10% of the residents live outside the village in small camps during the rainy season to farm. There is no access to the electrical grid and travel is by foot and bicycle on dirt roads. A market 35 kilometers 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$2,000, 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. Many families have a separate kitchen built from wattle and daub.

3.3.2. Initial planning visit

The initial planning visit focused on identifying village practices in energy supply and use, local artisans that use energy, and places where fuels are purchased or collected. A key goal of the initial planning visit was to choose five households to participate in the study and to conduct initial participant observations in these households. These observations were conducted between 5:00 a.m. and 10:00 p.m. The families were chosen based on family sizes, provided by an earlier survey of the village population. Income brackets were not considered during the selection process because the majority of household incomes are nonmonetary. 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%). One family was chosen from each stratum. Families were not selected at random, but rather selected to ensure that all energy applications and technologies could be observed during the planning period.

Energy supply pathways were defined by starting at the point of use and tracing the geographical route and physical mode of transport to the point of entry into the village. This included intermediate exchanges between people collecting or selling energy, and any temporary forms of storage (e.g., wood stocks and lead-acid batteries). The amount of standing wood in forests was judged to be sufficient for the near term (5–10 years) and was not surveyed. Energy use activities were organized into the following categories: domestic, artisan, public service, and transport. Energy derived from food calories, human activity, and animal activity was not included in the study.

3.3.3. Field studies

During the first field study, all village households were surveyed. This survey focused on (a) the type and quantity of energy-conversion technologies in the home, (b) the location of energy use activities, (c) the reasons for owning multiple technologies to meet the same energy need (e.g., three types of cookstoves or two forms of lighting), and (d) demographic information to assess changes in village population between seasons. Both the male and female heads of each family were interviewed. During each of the three field studies, surveys were completed for (a) the five participating families representing each village stratum, (b) village artisans and managers of public services, and (c) shop owners that sold petroleum fuels and disposable batteries. These surveys are summarized in Table 3.1.

Table 3.1. Survey information collected in each season.

Domestic	Artisans and Managers of Public Services	Convenience Shop Owners
Quantitative measurements of energy supply and energy use on a daily, weekly, and seasonal basis Rates of energy supply and energy use activities Advantages and disadvantages of energy sources and energy-related technologies Expressed energy needs Activity analysis of energy supply, storage, and use Energy use relative to other seasons and other years	Products or services provided Intended use or benefit of products or services Beneficiaries of products or services Price per product or service Activity analysis of energy supply, storage, and use Energy use relative to other seasons and other years	Location where the energy source was purchased, method of transport to the point of sale, unit size, and rate of energy purchase by the shop owner Rate of energy sales Unit size and price per unit Method of energy storage and method of transport after sale Energy sales relative to other seasons and other years

3.3.4. Measuring energy supply and use

Quantitative measurements of energy supply and use were completed for wood, charcoal, petroleum fuels, and electricity. Domestic wood use was given the most attention with a focus on cooking and heating water. Measurements were completed at the points of energy supply, storage, and use as indicated in Table 3.2.

3.3.4.1. Wood

Wood is used for multiple domestic and artisan applications. Data recorded on wood supply included (a) the location of wood collection, (b) the distance traveled to collect wood as determined by a handheld global positioning system, (c) the time spent collecting wood, (d) the mass of wood collected, (e) the rate of wood collection in one week, and (f) the demographic information of the person collecting wood. A total of 31 head-loads were measured for domestic wood collection. Five wood stocks were measured for mass and volume.

During the field studies, observations and measurements were made of domestic wood consumption for various tasks. Total measurements for all field studies included 35 one-day observations of cooking meals, 20 of space heating, 16 of water heating, seven of shea processing, six of peanut roasting, and three of making medicine. Each observation included measuring wood consumption and recording the wood type, technologies used, and number of people that benefited from the energy used. For each measurement a wood sample was gathered to determine moisture content [ASTM E870 2009]. Samples were gathered for all wood types to determine elemental composition, ash content, and higher heating value. More detailed information is available in [Chapter 4 this thesis]. The majority of tests were completed with the five participating families representing each village stratum, and tests from fourteen other families provided additional data from the village.

To simplify overall reporting of wood use on a village- or sector-wide basis 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.

Table 3.2. Measurements[a] and observations completed of energy supply, storage, and use.

Energy Source	Activity	Use Category	Measurements and Observations
Wood	Supply	Domestic	head-load
		Artisan	baker bike-load, blacksmith bike-load
	Storage	Domestic	wood stocks
	Use	Domestic	cooking, water heating, space heating, shea processing, peanut roasting, making medicine
		Artisan	baking bread, making snacks, heating tools for furniture making
Charcoal	Supply	Domestic	char remaining from cooking fires
		Artisan	char from above-ground controlled fire for blacksmithing
	Storage	Artisan	sacks for sale
	Use	Domestic	steeping tea
		Artisan	blacksmithing
Petroleum fuels	Supply	Domestic	kerosene, butane lighters, and candles
		Artisan	diesel for grinder
		Transport	gasoline for motorcycles
	Storage	Domestic	fuel container sizes
		Transport	fuel container sizes
	Use	Domestic	kerosene lighting, butane lighters, candles
		Artisan	grinder
Electricity	Supply	Domestic	daily log of lead-acid battery charges for a one-year period, disposable batteries, solar panel capacity
		Public service	solar panel capacity
	Storage	Domestic	disposable batteries
	Use	Domestic	lead-acid batteries, disposable batteries
		Public service	water pump, school lighting, mosque lighting, clinic lighting

[a]Equipment included a spring scale with 25 kg capacity and 500 g resolution, a digital balance with 25 kg capacity and 5 g resolution, a digital balance with 12.5 kg capacity and 2 g resolution, a digital balance with 5 kg capacity and 0.01 g resolution, a graduated cylinder with 100 mL capacity and 1 mL resolution, and a digital multimeter.

3.3.4.2. Charcoal

Charcoal is used by families for steeping tea and by the blacksmith. Charcoal production was measured by recording (a) the initial mass of wood, (b) the mass of charcoal created, and (c) the mass of wood remaining that was not converted to charcoal. A total of 61 measurements were taken for charcoal produced in domestic cooking fires. Two measurements of charcoal production by the blacksmith were made.

Domestic use of charcoal was calculated from three measurements of charcoal consumption and survey information on the daily rate of steeping tea for each family in the village. Charcoal consumption for blacksmithing was calculated using three measurements of charcoal consumption and survey data from the blacksmith during each field visit. Yearly representative charcoal lower heating values were determined using the same procedure as wood. These were 29.7 MJ kg^{-1} and 28.5 MJ kg^{-1} for the domestic and blacksmith charcoal, respectively.

3.3.4.3. Petroleum fuels

Petroleum fuels in the village included gasoline to power motorcycles, diesel to power the grinder, kerosene and candles for domestic lighting, and butane lighters to start fires. These fuels were sourced from markets by bus and sold to villagers at two local shops. Diesel consumption was measured over a total of seven grinding sessions and compared to estimates by the shop owners. Gasoline, kerosene, butane lighter, and wax candle consumption was measured at the point of sale. Energy use from petroleum fuels was calculated using the specific gravity of 0.750, 0.850, and 0.825, and the lower heating value of 43.5, 45.0, and 43.3 MJ kg^{-1} for gas, diesel, and kerosene, respectively [Ragland and Bryden 2011].

3.3.4.4. Electricity

Electricity in the village is used to power a water pump, household and public lighting, and household electronics. Electricity is supplied in three forms: (1) solar photovoltaic (PV) for water pumping, (2) solar PV charging station for rechargeable lead-acid batteries, and (3) disposable batteries.

The delivered electricity from solar PV was calculated using the rated panel power and an assumed annual capacity factor of 20%. All energy supplied by the panels was immediately used if no battery bank was connected for intermediate storage. If lead-acid batteries were connected to the panels, energy use from the 12 V 100 Ahr batteries was calculated using a mean of 87% recoverable energy [Stevens and Corey 1996], noting that this is approximate given the effects of self-discharge, deep discharge, and ambient temperature [Messenger and Ventre 2004, Ibrahim et al. 2008]. Detailed charging records were kept by the local battery charging business for each battery in the village. Disposable batteries are sold in the village with consumption rates calculated from weekly measurements during each field visit.

3.4. Results

3.4.1. Energy use

Village energy use is driven by basic domestic needs (i.e., cooking meals, heating water, and space heating), local manufacturing, transportation, and public services.

3.4.1.1. Domestic

Domestic energy use is comprised of wood consumption for cooking meals (52.2%), water heating (22.2%), space heating (19.1%), and other activities (6.5%). Wood use for cooking meals was estimated from a linear regression of energy use based on family size [Chapter 4 this thesis]. Demographic information was used to calculate daily energy use for cooking meals for each family over a year, and accounted for changes in family size due to seasonal migration. The total village energy use for cooking is 2.23×10^{6} MJ yr^{-1} (150,000 kg yr^{-1} of wood). This equates to an average wood use rate of 0.54 kg cap^{-1} day^{-1}.

In nearly all cases respondents bathed with hot water once per day. Typically, large cooking pots between 15 and 30 liters were placed on outdoor three-stone fires. Energy use was estimated by a linear regression based on family size over 17 observations [Chapter 4 this thesis]. The total village energy use for heating water is 947,000 MJ yr^{-1} (64,100 kg yr^{-1} of wood). This equates to an average wood use rate of 0.23 kg cap^{-1} day^{-1}.

Roasting peanuts and steeping tea were two forms of energy use observed in the study village that are not reported in other studies. Depending on the family, peanuts are roasted twice per week to once per month. Due to the variability, energy use for peanut roasting was measured separately from cooking meals, and estimated from a linear regression model of energy use based on family size over six observations [Chapter 4 this thesis]. The total village energy use for roasting peanuts is 106,000 MJ yr^{-1} (7,180 kg yr^{-1} of wood). The charcoal saved from cooking fires is used for steeping tea. Steeping tea uses an average of 53 g of charcoal $steep^{-1}$. The daily rate of making tea was recorded for each family across all seasons to calculate an annual energy use of 48,800 MJ yr^{-1} (1,640 kg yr^{-1} of charcoal).

Space heating begins mid-November and lasts until mid-February, with the coldest period in early January. All families used a primary heating fire, and about half of the families used a secondary heating fire for the elderly overnight. During the December field visit, energy use for space heating was measured with a mean and standard deviation of 130 and 42 MJ day^{-1} fam^{-1}, respectively. Families with a fire for the elderly used an additional 60 MJ day^{-1} fam^{-1} with a standard deviation of 8 MJ day^{-1} fam^{-1}. A focus group discussion found that peak wood consumption for space heating occurred in mid-January at approximately twice that observed during the field study period. Using this information, a linear interpolation was made to estimate daily energy use between November 15, with no energy for space heating, and January 15, with a peak of 260 MJ day^{-1} fam^{-1} for the primary fire and 120 MJ day^{-1} fam^{-1} for the secondary fire. Daily energy use for the primary fire was calculated for the 57 families present in the village during the cold season, and energy use for the secondary fire was calculated for the 24 families with elderly family members. A similar linear interpolation was performed from January 15 to February 15 when space heating ceased. Wood consumption was summed over these two periods to total 814,000 MJ yr^{-1} (55,100 kg yr^{-1} of wood).

Other domestic uses of wood include processing shea and making medicine. To extract the oil from shea nuts in this village, the nuts are heated in two phases during processing. The first includes heating the entire kernel in a smoker or boiling in a cooking pot. The second includes boiling a shea-water mixture to render the oil. Survey data indicated that the amount of shea processed varied widely among women, and subsequently no daily or weekly energy use values are reported. Local tests indicated that 6.4 kg of wood was used to produce one kg of shea oil; this is slightly lower than 8.5–10 kg of wood reported elsewhere [Niess 1988], and the lack of an intermediate roasting step often used to dry the shea meat may account for this difference. Surveys indicated that approximately one-half of adult and elderly women in the village processed shea. Using shea processing rates for each woman and the mean amount of wood consumption for each processing step, the village energy use for shea processing is 117,000 MJ yr^{-1} (7,950 kg yr^{-1} of wood). Shea is processed between July and October.

Families also used wood as an energy source for making medicine. This is done by steeping leaves and small branches in hot water. Medicine is most frequently made during the rainy and the cold seasons. Medicine for newborns is prepared the entire year. The average wood use for three tests, along with the rate of medicine production reported by each family, was used to calculate the total village energy use for medicine to be 55,600 MJ yr^{-1} (3,760 kg yr^{-1} of wood).

Kerosene used in household lighting was calculated from monthly consumption data provided by shop owners. Village kerosene consumption is 40 liters mo^{-1}, or 480 liters yr^{-1} with a total yearly energy use of 17,100 MJ yr^{-1}.

The yearly electrical use rate is 3240 MJ yr^{-1} from rented lead-acid batteries that are charged at a local battery charging station using solar PV, and 1,730 MJ yr^{-1} from privately owned lead-acid batteries and solar PV. Shops selling petroleum fuel indicated that kerosene sales have dropped by about half following the introduction of household electrical lighting systems two years before the study, suggesting that the current lighting program in the village has displaced approximately 17,000 MJ yr^{-1} of kerosene. Portable lanterns, flashlights, and radios that use disposable batteries had a negligible contribution to village energy. Energy use from butane lighters and wax candles was negligible.

3.4.1.2. Artisans

The commercial sector in the village is comprised of artisans and a few local enterprises that provide many of the products used in the village. Five women in the village fry small snacks for sale with an average wood use per session of 2.0 kg and a range of 1.6 to 2.3 kg from three observations. The yearly energy use for making snacks is 57,400 MJ yr^{-1} (3,890 kg yr^{-1} of wood).

The baker makes bread using a wood-fired oven. Demand for bread is highest during the farming season when villagers have little time to make breakfast before going to the fields. Following harvest, bread demand is at its lowest because families have more time to prepare their own meals. One firing consumes an average of 31 kg of wood with a range of 22 to 37 kg measured over six observations. In one year, the baker uses 26,900 MJ yr^{-1} of energy (1,820 kg yr^{-1} of wood).

A local furniture maker heats carpentry tools over a wood fire that uses an average of 8.1 kg day^{-1} over three observations. Working every day from February 1 to May 31, the furniture maker uses a total of 14,900 MJ yr^{-1} (1,000 kg yr^{-1} of wood).

The blacksmith uses charcoal to form a variety of items for local use (e.g., farm tools, wood axes, buckets, and knives). Charcoal use is measured by the charge. A charge is an average 6.6 kg of charcoal with a range of 6.4 to 7.1 kg measured over five observations. Peak charcoal use occurs from April 1 to May 31 at three charges day^{-1} when the blacksmith is preparing farming tools before the planting season starts in June. From June 1 to September 30, the blacksmith farms and only uses three charges week^{-1}. He performs no blacksmithing during harvest (October 1 to December 15). Following harvest, the blacksmith uses two charges week^{-1} from December 16 to March 31. Energy use for blacksmithing is 50,200 MJ yr^{-1} (1,760 kg yr^{-1} of charcoal). The charcoal is produced from 8,390 kg yr^{-1} of wood.

One diesel-powered grinder is available in the village to process corn, millet, peanuts, rice, and shea. Estimates of diesel consumption by the operator were verified with seven daily measurements spread across the primary field visits. Diesel consumption is five liters week^{-1} from January 1 to June 30, and eight liters week^{-1} from July 1 to December 31 as demand for the grinder increases to process shea. Grinding accounts for 13,000 MJ yr^{-1} (340 liters yr^{-1} of diesel).

3.4.1.3. Public services

Public uses of energy include powering a pump for clean drinking water and lighting public buildings. The village has no energy utilities and no factories. The water pump is powered by a solar PV array with a total rated capacity of 1,325 W. There is no battery bank. There is no float in the water tank to indicate when it is full, and the pump operates whenever the minimum panel voltage is met. Assuming a 20% capacity factor, the electrical use for the water pump is 8,400 MJ yr^{-1}.

Lighting at the medical clinic is provided by a solar PV array that charges a battery bank. The battery bank was completely depleted at the end of each day prior to the recent introduction of one additional battery. One light remains on all night to indicate the location of the medical clinic, and several lights inside the building are used intermittently. Assuming that the electricity generated by the solar PV array was used each day, and assuming a 20% capacity factor, the yearly electrical use for the clinic is 3,500 MJ yr^{-1}.

The primary school has three solar panels with a total rated capacity of 225 W. Each solar panel charges a lead-acid battery that powers two 10 W linear fluorescent bulbs. For approximately six months, the batteries are completely drained in the evening after receiving a partial charge during the day. Assuming a 20% capacity factor for the six months of use, the yearly electrical use for the school is 710 MJ yr^{-1}.

3.4.1.4. Transport

Motorcycles are the only form of motorized transportation owned and operated by people in the village. All gasoline sales are attributed to motorcycle use. Gasoline consumption was measured at the point of sale. The two convenience shops sold 125 liters $week^{-1}$ in January and February, 100 liters $week^{-1}$ from March to May, and 60 liters $week^{-1}$ from June to December. Sales are higher in January and February following harvest when families have sold grain and have more disposable income. The gasoline consumption rate for transport is 4,200 liters yr^{-1}, equivalent to 137,000 MJ yr^{-1}.

3.4.2. Energy supply

Energy is supplied to the village from three sources: (1) wood and charcoal from the forest, (2) electricity from solar PV panels, and (3) petroleum-based fuels and disposable batteries from outside of the village.

3.4.2.1. Wood

Women and children walk three to eight kilometers round-trip to gather wood from family farms. This behavior is contrary to village energy models that assume wood is gathered in a concentric ring surrounding the village, and that over time forest resources dwindle near the village, requiring additional time to gather wood [Hartter 2007]. Interviews indicated that the time needed to gather wood had not increased in the past ten years, suggesting that the distributed harvesting behavior in the study region had not increased collection time in the short term.

Wood is carried on the head in bundles that range from 3 to 11 and 14 to 22 kg trip^{-1} for children and adult women, respectively. It takes an average of two hours to walk to the fields, harvest wood, and return home with one load based on four observations. Green wood is rarely harvested. The higher moisture content makes the wood heavier to transport and harder to burn in small fires. In rare instances, a donkey and cart are hired to transport 150–200 kg trip^{-1}. Village artisans transport wood by lashing bundles across bicycle racks.

Wood collection rates fluctuate during the year, closely following precipitation and farm activity. A typical yearly collection cycle is shown in Fig. 3.2. Women are responsible for stockpiling wood for kitchen use during the dry season. They do not collect wood during the rainy season because of farming responsibilities. Each woman has her own stockpile of wood that ranges from 500 to 800 kg. The month of March is commonly reserved for rest and no wood is collected. Wood collection peaks between April and July. A similar seasonal behavior in wood collection has also been seen in Zimbabwe [Gill 1983], although the collection period in Zimbabwe is from June to October.

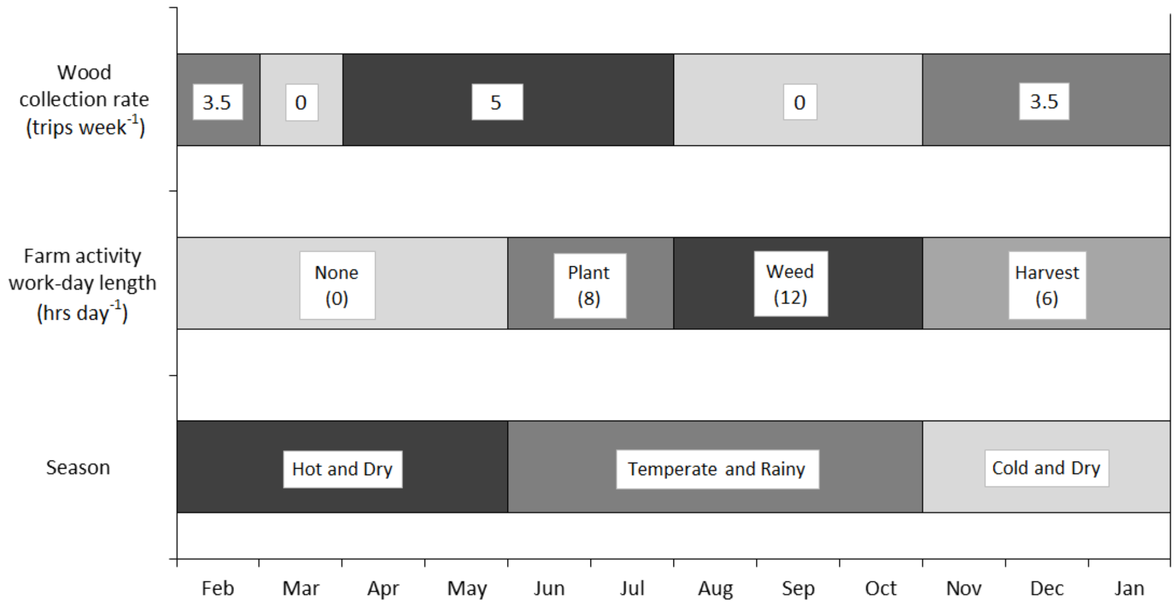

Figure 3.2. Yearly cycle for wood collection, farming, and seasons.

3.4.2.2. Charcoal

Charcoal used in the village is produced in two ways: in household cooking fires by dripping water over embers after cooking meals and in controlled above-ground fires where the blacksmith chips away the char layer from burning wood. Table 3.3 shows the charcoal yield for each production method. The difference in charcoal yield between households and the blacksmith is caused by the different production methods.

Table 3.3. Dry charcoal yield by mass of dry wood (%).

Producer	Production method	Average (range)	Number of observations
Household	Cooking fire	10.6 (2.5 – 29.0)	61
Blacksmith	Controlled above-ground fire	23.7 (21.7 – 25.7)	2

3.4.2.3. Electricity

As discussed earlier, the village has 41 solar PV panels with a total rated capacity of 2.92 kW. The water pump is powered by a solar PV array with a rated capacity of 1,320 W. All other panels in the village charge lead-acid batteries for intermediate storage. The rated capacity of these panels include a primary school at 225 W, a medical clinic at 560 W, a battery charging business at 540 W, and privately owned panels totaling 275 W. Disposable batteries for portable electronic devices are sold in the village.

3.4.2.4. Petroleum fuels

Petroleum fuels are sold in shops in the village. Shop owners travel to the market once per week to order supplies and receive shipments by bus that same evening. Orders are delivered in bulk and split into smaller units for sale. Sales of most petroleum fuels are higher in the cold season because villagers have more disposable income from selling recently harvested grain.

3.4.3. Discussion of results

Total annual village energy use is 4.61×10^6 MJ yr^{-1}, or approximately 6,000 MJ cap^{-1} yr^{-1}. Figure 3.3 shows a breakdown of village energy supply and use. Wood is the primary energy source, and the majority of energy is used for domestic needs. Gasoline is the primary petroleum product and is used only for transportation. Kerosene is used for lighting and diesel is used for the grinder. Wood and charcoal provide 99% of domestic energy and 90% of artisans' energy. Public services use solar PV for all energy needs. Figure 3.4 shows the monthly energy use for each end-use category. It is apparent that village energy use reaches a maximum in the cold and dry season due to domestic energy use for space heating (Fig. 3.5). There is a slight increase in village energy use during April and May due to the blacksmith forging tools in preparation for the farming season. Domestic energy use decreases from May to June due seasonal migration away from the village to small farms. The increase in domestic energy use during the latter half of the rainy season is due to shea processing. Artisans' energy use varies by 350%, and energy use for transportation varies by 210% during the year. The seasonal changes in energy use for public service are minimal.

The annual domestic wood consumption is 375 kg cap^{-1} yr^{-1}. This is in the lower quartile of annual per capita consumption values reported in other rural energy studies in sub-Saharan Africa, and similar to other values reported for Mali and nearby Burkina Faso (Fig. 3.1). Average daily wood consumption is 1.03 kg cap^{-1} day^{-1}. However, seasonal consumption shows a minimum of 0.79 kg cap^{-1} day^{-1} in the hot season and a maximum of 2.41 kg cap^{-1} day^{-1} in the cold season. The additional wood consumption in the cold season is due to space heating, accounting for a three-fold increase in per capita wood consumption. Figure 3.5 shows domestic wood consumption calculated for a family of 13 people that processes shea and has an elderly adult present in the home. This is near the mean family size of 12.8 people fam^{-1}. The wood consumption for this family is approximately five tons yr^{-1}, or 1.08 kg cap^{-1} day^{-1}. Space heating is not used for much of the year, but it is the largest contributor to domestic wood consumption in the cold season. Wood use for shea processing consumes 30.2 kg mo^{-1} to dry kernels and render oil for most of the rainy season. Energy use for heating water remains fairly steady throughout the year, but can fluctuate between the hot and cold seasons depending on family preference. In the rainy season, medicine for malaria is made once every two weeks. In the cold season, medicine is made each day for a one-week period to treat cold or flu. Using the same assumptions, wood consumption for families of size 5, 10, 20, or 40 people is 2.04, 1.26, 0.87, and 0.68 kg cap^{-1} day^{-1}, respectively.

Additionally, the following conclusions can be drawn from the study:

- Cooking meals accounts for approximately one-half of village energy use (48.3%). All women use more than one cookstove. In many cases, these are multiple three-stone fires. One-half of the women use more than one type of cookstove and commonly use different types of cookstoves for different tasks. Meal size varies from 1.3 to 24.7 kg for the total mass of wet and dry ingredients. This suggests that one type of cookstove is unlikely to meet the cooking needs of the village.
- Improved cookstove designs can provide a 40% reduction in wood energy use compared to traditional fires [MacCarty et al. 2010]. Thus, the introduction and adoption of improved cookstoves could reduce wood energy use by approximately 20% (0.40 × 0.48). Heating water comprises 20.5% village energy use. Hence, if solar water heaters were introduced and adopted, this would result in the same level of reduction in wood use as the introduction of improved stoves.
- Space heating accounts for 17.6% of village energy use. Space heating begins mid-November and ends in mid-February. The highest space heating needs are in early

January when each family uses multiple fires to heat their home in the morning, evening, and in some cases through the night.

- Wood consumption per capita decreases with increasing family size. This is more significant for smaller families than for larger families.
- Wood is gathered from family farms that are 1.5 to 4 km from the village. This behavior is contrary to village energy models that assume wood is gathered in a concentric ring around the village, and that over time forest resources dwindle near the village [Hartter 2007].
- Domestic wood collection requires an average of 250 hrs cap^{-1} yr^{-1} for approximately 120 women, and an average of 40 hrs cap^{-1} yr^{-1} for approximately 250 children.
- Families use multiple sources of energy in the home, including wood, charcoal, kerosene, and electricity (disposable and rechargeable batteries). There is no indication that families are following an "energy ladder" in which households are expected to gradually progress from using low-quality fuels such as biomass to higher-quality fuels such as electricity and liquefied petroleum gas [Hosier 2004]. Domestic energy use better resembles "fuel stacking" in which consumers use multiple fuels without displacing the use of traditional fuels [Hiemstra-van der Horst and Hovorka 2008].
- Approximately half of village electricity is used for lighting, and the other half is used for the village water pump. Some families also use personal electronic devices, such as cell-phones and radios. These devices are a small but important type of village electricity use.

- Total domestic expenditures on energy sources amount to US$5,870 yr^{-1} for the village or US$1.88 fam^{-1} $week^{-1}$. This is a significant expenditure relative to the income of subsistence-level farmers in the village. Disposable batteries account for 65% of all domestic energy expenditures, followed by lead-acid battery rental and charge (23%) and kerosene (12%).
- Although disposable batteries provide a minor contribution to total village energy, they are a significant expense. This expense reflects the importance of small electronics to the village. In addition, disposable batteries are a significant environmental hazard. Each year 21,000 disposable batteries are discarded in the village.

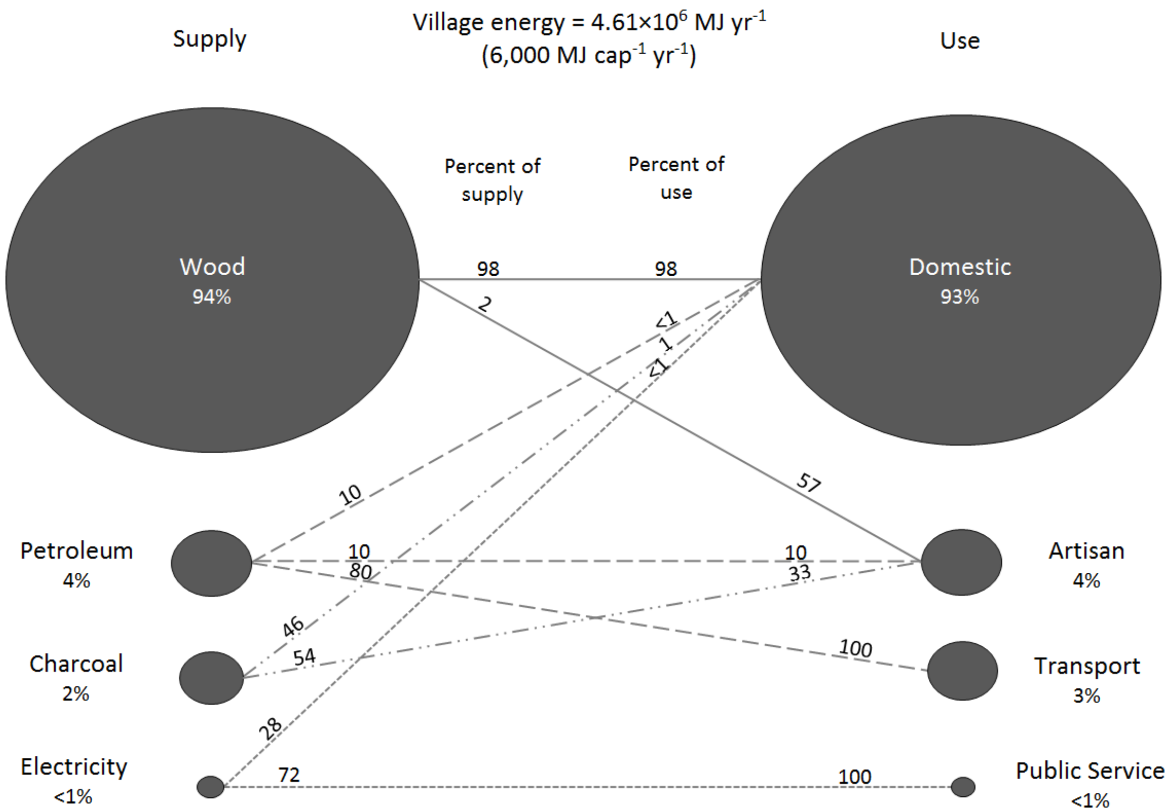

Figure 3.3. Village energy supply and use by percentage.

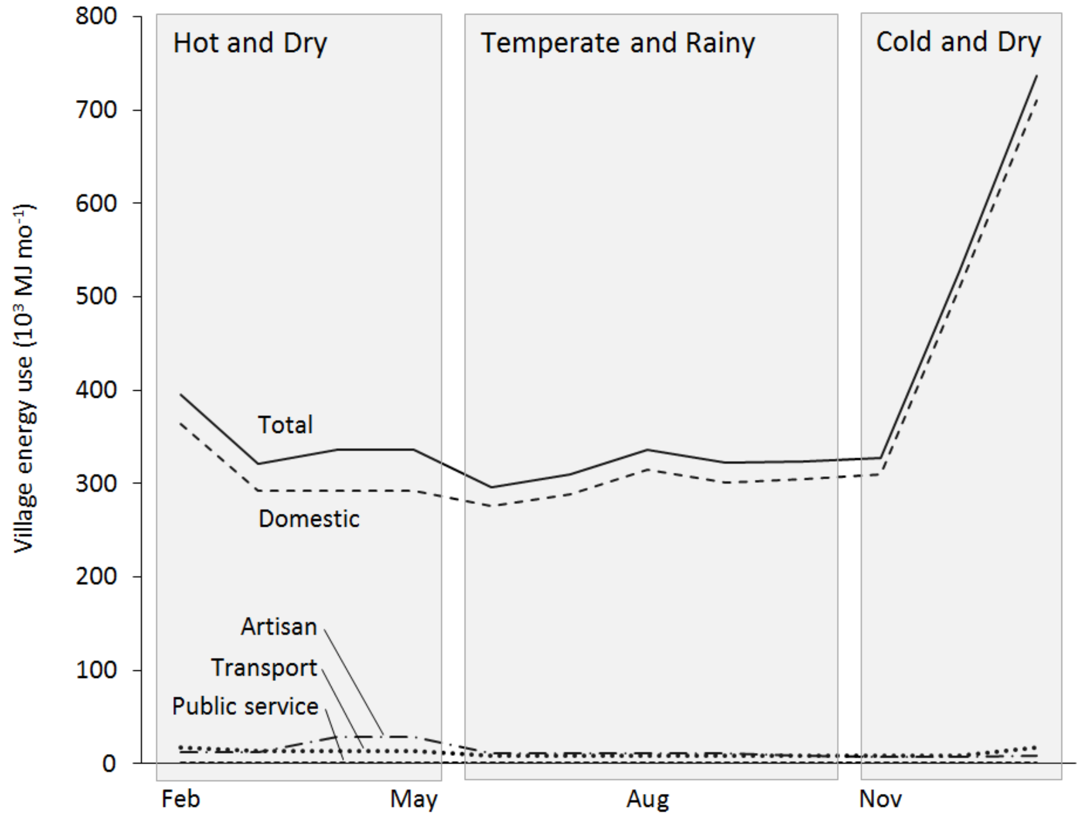

Figure 3.4. Variation in energy use across one year. Seasons are shown as shaded boxes.

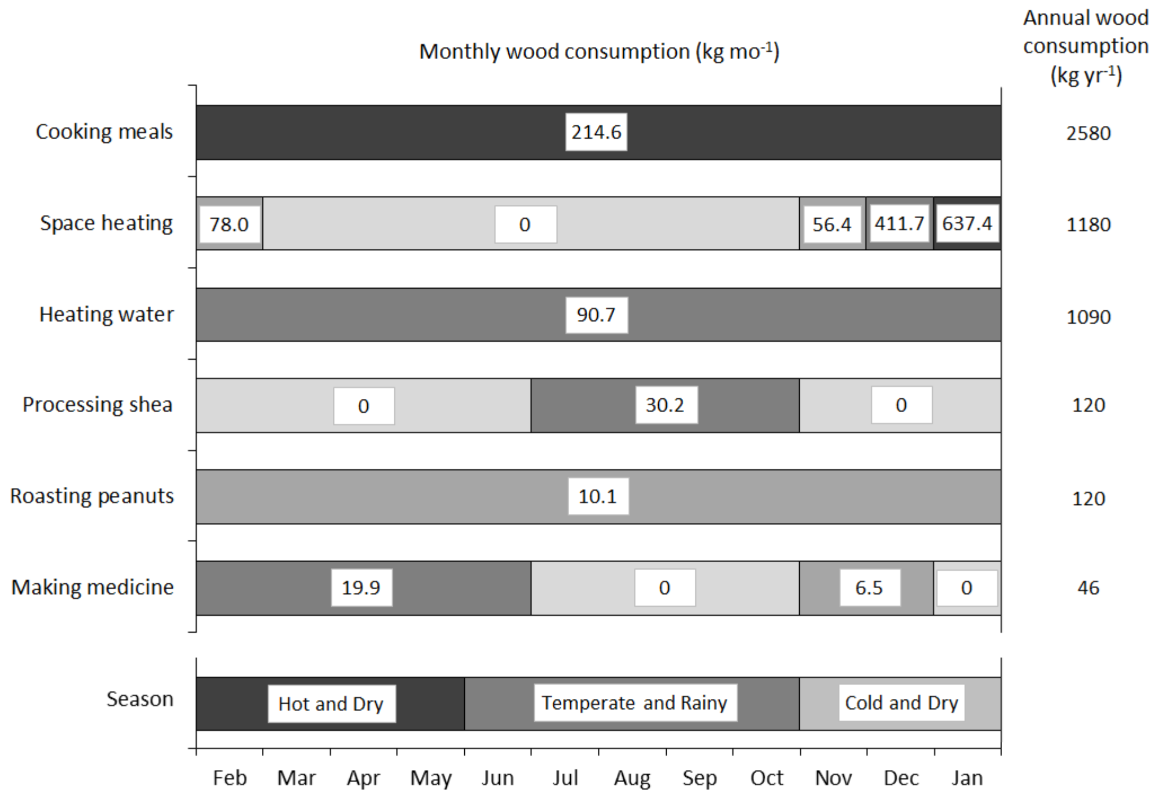

Figure 3.5. Wood consumption by activity for a family of 13 people.

3.5. Conclusions and future work

This paper presents the results of a novel study of energy supply and use over a one-year period in an isolated rural village in Mali. Energy supply and use within the village is driven by human, natural, and engineered systems. Wood is the primary energy source, providing 94% of village energy. Approximately 98% of this wood is used to meet domestic energy needs. Gathering wood is a significant time investment of 250 hrs cap^{-1} yr^{-1} and 40 hrs cap^{-1} yr^{-1} for women and children, respectively. The uses of wood in the home are cooking (52.2%), heating water (22.2%), space heating (19.1%), and other activities (6.5%). Electricity is a small but important energy source to the village. Water pumps, lights, and personal electronics are powered by solar PV, rechargeable batteries, and disposable batteries. Disposable batteries account for 65% of all domestic energy expenditures. The largest and smallest energy sources in the village, wood and electricity, respectively, provide vital functions—cooked meals, hot water, warmth, clean water, lighting, and power for small electronics. A sustainable energy solution for this village and similar villages will need to address these six areas using a systems-based approach that recognizes how energy supply and use are an integral part of village life and economy.

The long-term objective of this work is to develop the understanding and tools needed to design and implement sustainable energy solutions for rural villages. Planned future work includes studying energy dynamics in other villages in West Africa. Beyond this, additional studies are needed to examine and understand energy supply and use within rural villages across the world.

Acknowledgments

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CHAPTER 4

FACTORS AFFECTING FUELWOOD CONSUMPTION FOR COOKING IN AN ISOLATED RURAL WEST AFRICAN VILLAGE

A paper to be submitted to *Energy*

Nathan G. Johnson, Kenneth M. Bryden

Abstract

This study examines the factors that affect fuelwood consumption for cooking and estimates fuelwood use for cooking in a rural isolated West African village with a population of 770. Sixteen factors were examined during four field studies that were completed over a one-year period. Multiple regression analysis identified six of these factors 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 cooking totaled 234 metric tons ; cooking meals and heating water accounted for 65% and 27%, respectively. Fuelwood consumption per person was strongly linked with family size. As family sized increased from five to twenty members fuelwood consumption decreased from 20.6 MJ cap^{-1} day^{-1} to 10.5 MJ cap^{-1} day^{-1}. Within the village, 52% of cooks used only one cookstove, 36% used two cookstoves, and 12% used three or more. Strong evidence was found of "stove stacking" in which improved stoves are used as additional cooking resources rather than replacing existing cookstoves. The type of cookstove had limited impact on fuel consumption at the lowest level of significance (90%) after accounting for other factors for one type of stove. Analysis of the results indicated that other types of stoves may impact fuel

consumption but the effect was not statistically significantly in this study. This suggests that additional multifactorial studies focused on the impact of improved stoves on fuelwood consumption for cooking are needed.

Key Words

Cooking, cookstove use, wood consumption, rural Africa, multiple regression, stove stacking

4.1. Introduction

Biomass cookstoves are common in households throughout the developing world and have significant health, safety, and environmental consequences [Bond and Sun 2005, Desai et al. 2004, Johnson 2005, Manibog 1984, Ramanathan 2008, Smith et al. 2004, Wickramasinghe 2003, World Health Organization 2009]. 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 [Al-Soud et al. 2010], solar hybrids [Prasanna and Umanand 2011a], off-grid PV solar community kitchens [Prasanna and Umanand 2011b, Dufo-López et a. 2012] and biogas digestors [Ding et al. in press]. Other efforts have also suggested focusing on shifting to low-emission liquid or gaseous fuel cookstoves [Reddy et al. 2000]. However many communities have existing distribution networks for wood and other solid biomass fuels and continue to use traditional biomass cookstoves. As a consequence there is a significant ongoing effort to develop and distribute improved biomass cookstoves. To date, improved cookstoves have been distributed to nearly 830 million of the three billion people using solid fuels for cooking in developing countries [World Health Organization and United Nations Development

Programme 2009]. With this introduction of cookstoves, significant attention has been given to understanding the factors that impact cookstove performance and comparing the performance of various cookstoves [Adkins et al. 2010a, Adkins et al. 2010b, Bailis et al. 2007, Baldwin 1987, Ballard-Tremeer and Jawurek 1996, Berrueta et al. 2008, Bhandari et al. 1988, Bhattacharya et al. 2002, Boy et al. 2000, Bussmann et al. 1983, Claus and Sulilatu 1982, Dutt 1981, Geller 1982a, Geller 1982b, Gill 1983, Gill 1987, Granderson et al. 2009, Jetter and Kariher 2009, MacCarty et al. 2010, McCracken and Smith 1998, Miah et al. 2009, Mukunda et al. 1988, Prasad et al. 1985, Smith et al. 2007]. However, only a small number of studies have examined the relationship between fuel consumption and factors other than cookstove design and type [Adkins et al. 2010a, Adkins et al. 2010b, Bhattacharya et al. 2002, Boy et al. 2000, Geller 1982a, Jetter and Kariher 2009, Miah et al. 2009]. This study examines the factors that impact fuelwood consumption for cooking in a rural isolated West African village and estimates fuelwood use for all types of cooking. All methods and data discussed in this paper were approved by the Institutional Review Board at Iowa State University.

4.2. Background

A number of laboratory and field studies have examined the performance of biomass cookstoves in the developing world. Commonly, the results from laboratory and field studies show little agreement [Bailis et al. 2007, Berrueta et al. 2008, Geller 1983, Gill 1987, Manibog 1984], and, as a result, there is no laboratory substitute for field study. 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 [Bailis 2004]. The KPT is used to compare cookstoves using in-home cooking tests in which the meals are selected and prepared by users [Bailis 2007]. 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 [Baldwin 1987, Joseph 1990]. Other standardization methods have been proposed, as reviewed by Howes [Howes 1985].

Several studies have reported factors other than cookstove type that effect energy use for cooking [Adkins et al. 2010a, Adkins et al. 2010b, Bhattacharya et al. 2002, Biswas and Lucas 1997, Boy et al. 2000, Geller 1982a, Hosier 1984, Hosier 1986, Jetter and Kariher 2009, Kersten et al. 1998, Marufu et al. 1997, Miah et al. 2009, Reddy 1982, Vermeulen et al. 2000, Visser 1982]. Studies in India using simple linear regression found moderately strong correlations between meal size and cooking energy use (R^2 = 0.77) [Geller 1982a], and annual total cereal consumption and cooking fuelwood consumption (R^2 = 0.77) [Reddy 1982]. 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) [Adkins et al. 2010a]. A study in Bangladesh reported that family size was positively correlated to daily fuel consumption (R^2 = 0.79) [Miah et al. 2009]. 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 ($R^2 = 0.71$) [Biswas and Lucas 1997]. 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 [Hosier 1984]. 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 sixteen factors that may affect energy use for cooking in a rural isolated West African village. In contrast to studies that compare cookstoves, the goal of this study was to identify and understand all factors that affect fuel consumption for cooking. Multiple regression analysis was used to directly analyze cooking energy use. Three different tests were designed and used to gather data. These methods are contrasted, and a methodology for estimating fuel usage in this and similar villages is developed.

4.3. 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 to May); rainy and humid with moderate temperatures (June to October); and cool and dry (November to January). Approximately two-thirds of Mali's 13 million people live in rural areas [World Bank 2008].

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 [Klugman 2010]. On a national level, biomass accounts for 78% of energy use [SIE-Mali 2007], and over 99% of households use solid fuels for domestic energy needs [World Health Organization 2003]. The national per capita energy use of 7,500 MJ cap^{-1} yr^{-1} is one-third of the average in Africa [SIE-Mali 2007].

The village has sixty 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 to farm. 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$2,000, 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.

4.4. 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.

4.4.1. 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 cook. The women responsible for cooking were interviewed to determine (a) the type and quantity of cookstoves owned, (b) the location of cooking, (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 cooking were completed for all cooking activities. 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 cooking activities 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 and brevity. These findings include

1. <u>Cookstoves:</u> There are six types of cookstoves in the village, as shown in Fig. 4.1: (a) a traditional three-stone fire, (b) a traditional gakourouwana cookstove with one or more cooking hobs, (c) a low thermal capacity cookstove made from clay and straw

blocks, (d) a hand-crafted metal cookstove made in Mali for cooking meals, (e) a manufactured metal 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 at no cost to the user one to two years before this study.

2. Cookstove ownership: As shown in Table 4.1, 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. Over one-third of the women share cookstoves (38.2%). All families own at least one small charcoal stove for steeping tea.

3. Cookstove use: The three-stone fire is used for nearly all cooking 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.

4. Cookstove applications: Cookstove applications include six meal types and five non-meal cooking applications (Table 4.2). Two meal types are commonly eaten for breakfast and four meal types are commonly eaten for lunch and dinner. Most meals include porridge. Modifications to these basic meals include changing the grain type (corn, millet, rice) or changing the sauce type (leaves, peanut, okra,).
5. 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.
6. Meal composition: The percentage of dry ingredients to the total meal mass ranged from 9.7% to 26.8% for breakfast porridge meals, 17.0% to 32.1% for lunch and dinner meals with porridge and sauce.
7. Cooking vessels: The only type of cooking vessel in the village is an aluminum pot that ranges in capacity from 1 to 50 liters.
8. Fuel use: Cooking meals and heating water are the primary contributors to domestic cooking fuelwood consumption.
9. Fuel properties: Eight types of wood were commonly used as fuel. Wood varied in thickness from less than one centimeter to more than ten centimeters in diameter.
10. 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.

11. 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.
12. 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.
13. Cooking practices: Women spend up to 20 minutes 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.
14. 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 charcoal from another cooking fire.

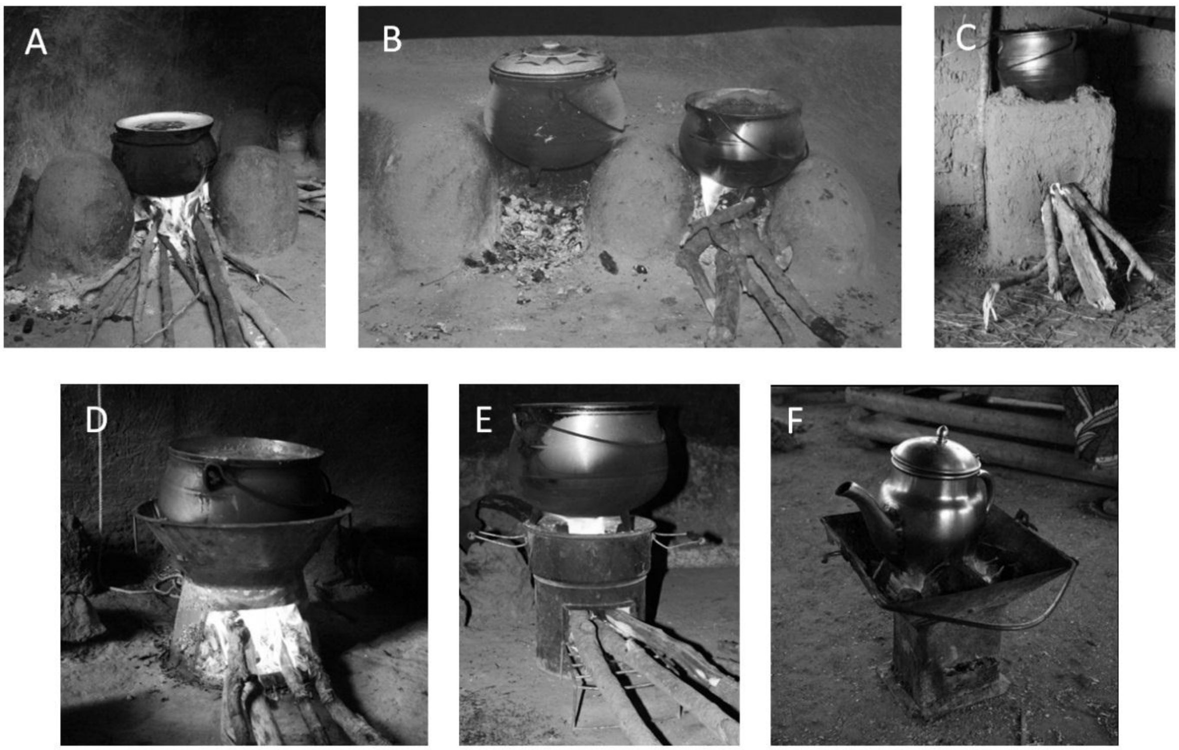

Figure 4.1. Cookstoves in the village: (A) three-stone fire, (B) gakourouwana, (C) low thermal capacity, (D) hand-crafted metal, (E) manufactured metal, and (F) charcoal tea.

Table 4.1. Cookstove ownership in the village.

Number of cookstoves (% of total cooks)[b]	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%)

[a]Three stone fire (TSF), gakourouwana (GK), low thermal capacity (LTC), hand-crafted metal (HCM), manufactured metal (MM).
[b]Percentages in left column do not add to 100% due to rounding.

Table 4.2. 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).

4.4.2. Cooking studies

Cooking studies were completed during three four-week field visits. Findings from the planning study suggested that the following seventeen 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 4.3 were gathered for the 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, the mass of the cooking vessel, and the ambient temperature 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.
- The Session Cooking Test (SCT) measures the mass of fuel, the mass of all meal ingredients, the ambient temperature at the beginning of the cooking session, 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 are also recorded. A researcher is not present during the cooking session.
- The Daily Cooking Test (DCT) measures fuel consumption once per day by weighing separate stacks of wood that have been set aside for each cooking event (e.g., breakfast). 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.

Table 4.3. 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 Ambient temperature 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 Meal time of day	Cookstove application Cooking ingredients Cookstove type Number of cooking fires Wood name Season Ignition method Cooking location Meal time of day	Cookstove application Cookstove type Wood name Season Cooking location Meal time of day

Categorical data was also recorded such as cookstove type, the number of cooking fires, and local wood names. As shown in Tables 4.4 and 4.5, 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 4.4). 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 sixty 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.

Table 4.4. Household cooking tests for meals.

	Family ID																			
Test	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Totals
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

Table 4.5. Household cooking tests for non-meal cookstove applications.

	Cookstove application[a]						
Test	WH	RP	MM	BK	RO	ST	Totals
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).

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 nonstandardized process that can introduce significant error in energy calculations [Taylor 2009].

4.4.3. 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 4.6. 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 4.7. Moisture content does not 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 properties were determined for each wood species (Table 4.8). 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.

Table 4.6. 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	Baking; Domestic cooking and heating
Prosopis cf. africana	Guele	Charcoal production
Pterocarpus aff. erinaceus	Gendu	Domestic cooking and heating
Pterocarpus cf. lucens	Barra	Domestic cooking and heating
Cola nitida	Woro	Domestic cooking and heating; Charcoal production
Char (Prosopis cf. africana)	Finfing	Blacksmithing
Char (Pterocarpus aff. erinaceus)	Finfing	Steeping tea

[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 [Widenhoeft 2006].

Table 4.7. Seasonal variation in wood moisture content on an as-received basis (wt %) [ASTM E870].

Month samples acquired	Weather description	Mean (range)	Number of samples
May	Hot and humid, no rain	10.9 (10.2 – 12.2)	7
August	Hot and humid, rain	18.3 (13.6 – 43.1)	15
December	Cool and dry	7.7 (6.2 – 12.9)	13

Table 4.8. Proximate analysis, ultimate analysis, and higher heating value (HHV) tests for wood and charcoal samples. Values reported on dry, ash-free basis [ASTM E870].

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

4.5. 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.

4.5.1. 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 (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 4.9. Categorical variables were cast as dummy variables. The Akaike information criterion (AIC) was used to guide estimator selection [Akaike 1974]. 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 4.10 lists models 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. (4.18) 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 represented as a third dummy variable. Interaction variables were not found to improve model fit.

Table 4.9. Estimators tested in multiple regression models of energy use $family^{-1}$ $meal^{-1}$.

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]	Meal type	Breakfast porridge (thin), Breakfast porridge (thick), Meal porridge (thin) with sauce, Meal porridge (thick) with sauce, Couscous
Mass water	Meal time of day	Breakfast, Lunch, Dinner
Mass dry ingredients	Grain type	Corn, Millet, Rice
Mass total ingredients (initial)	Sauce type	Leaves, Peanut, Okra
Wood moisture content	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), female over 14 yr (0.8), male 15-59 yr (1.0), male over 59 yr (0.8) [Baldwin 1987, Joseph 1990].

Multiple regression analysis of data on a per meal basis indicated the following findings from the equations listed in Table 4.10

- Of the two key continuous variables tested, the mass of total meal ingredients in Eq. (4.15) performed much better than family size in Eq. (4.21) at explaining variation in the dataset.
- The mass of dry ingredients in Eq. (4.8) is a better estimator of energy use than the total mass of dry ingredients and water in Eq. (4.15) or the mass of water in the meal Eq. (4.19). 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 meal type, Eqs. (4.4) and (4.7), and improved further by accounting for the ignition method, Eqs. (4.1) and (4.2). In all cases, meals with a sauce component use more energy to cook than other meals (32% increase using Eq. (4.4)). The dummy variable for couscous is not significant when using dry mass in Eq. (4.4), but is significant during a regression on total mass in Eq. (4.7). The difference in significance occurs because couscous is steamed, and the total mass of couscous is only the dry grain, whereas the total mass of other meals includes dry and wet ingredients.
- Including family size (Eq. (4.3)) in the regression with the mass of dry ingredients and meal type (Eq. (4.4)) 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 of each meal type in Eqs. (4.9) and (4.10) improves model fit over the regression with no differentiation between meals in Eqs. (4.8) and (4.15). However, the regression including dry ingredients (Eq. (4.9)) 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 in Eqs. (4.6), (4.11), (4.14), and (4.18), 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. (4.18)). The manufactured metal cookstove decreased wood consumption by 25% but not at a statistically significant level (Eq. (4.18)).
- The use of burning embers as an igniter is significant in Eqs. (4.1), (4.2), (4.5), (4.12) and (4.13) 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 (equivalent to 530 g of as-received wood), 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. (4.11), (4.13), and (4.20)) by approximately 26% (Eq. (4.13)).
- 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 additionally 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 meal time of day.

Table 4.10. Multiple regression models of energy use family^{-1} meal^{-1}.

EQ	Estimators	R^2	AIC
4.1	$19.74^{***}+7.23^{***}m_{dry}+10.10^{**}M_{sau}-8.16^{**}I_{char}$	0.7188	430.5
4.2	$14.83^{***}+2.04^{***}m_{tot}+12.56^{***}M_{sau}+13.01^{*}M_{cous}-8.69^{**}I_{char}$	0.7100	434.2
4.3	$10.20^{**}+6.15^{***}m_{dry}+0.47^{\dagger}n_p+10.17^{**}M_{sau}$	0.6898	436.1
4.4	$14.49^{***}+7.31^{***}m_{dry}+9.31^{**}M_{sau}$	0.6690	437.9
4.5	$20.59^{***}+9.16^{***}m_{dry}-7.41^{*}I_{char}$	0.6606	439.3
4.6	$7.32^{*}+2.19^{***}m_{tot}+11.76^{***}M_{sau}+11.84^{*}M_{cous}+7.93^{\dagger}S_{LTC}$	0.6733	441.1
4.7	$9.33^{**}+2.04^{***}m_{tot}+11.95^{***}M_{sau}+13.31^{*}M_{cous}$	0.6537	442.5
4.8	$15.74^{***}+9.10^{***}m_{dry}$	0.6193	444.0
4.9	$16.91^{***}+8.21^{***}m_{dry,gra}+10.87^{***}m_{dry,sau}+5.01^{*}m_{dry,cous}$	0.6434	444.2
4.10	$14.31^{***}+1.53^{**}m_{tot,gra}+4.97^{***}m_{tot,sau}+6.07^{*}m_{tot,cous}$	0.6334	445.8
4.11	$10.35^{**}+2.35^{***}m_{tot}+7.65^{*}N_f+8.82^{\dagger}S_{LTC}$	0.6172	448.3
4.12	$18.79^{***}+2.45^{***}m_{tot}-8.17^{*}I_{char}$	0.5975	449.2
4.13	$13.00^{***}+2.15^{***}m_{tot}+8.06^{*}N_f$	0.5924	450.0
4.14	$10.73^{**}+2.61^{***}m_{tot}+9.59^{\dagger}S_{LTC}$	0.5770	452.1
4.15	$13.65^{***}+2.41^{***}m_{tot}$	0.5475	454.0
4.16	$15.13^{**}+0.99^{***}n_p+19.81^{***}M_{sau}-6.41^{\dagger}I_{char}$	0.5763	454.2
4.17	$7.10^{\dagger}+1.16^{***}n_p+20.75^{***}M_{sau}+10.10^{\dagger}M_{cous}$	0.5700	455.1
4.18	$10.77^{*}+2.66^{***}m_{tot}+1.69S_{GK}+9.32^{\dagger}S_{LTC}-1.58S_{HCM}-8.12S_{MM}-2.53S_{MULT}$	0.5969	457.3
4.19	$15.95^{***}+2.81^{***}m_w$	0.4487	465.5
4.20	$11.19^{*}+1.33^{***}n_p+15.72^{***}N_f$	0.4430	468.1
4.21	$16.30^{**}+1.37^{***}n_p$	0.2484	483.5

Signficance for each estimator is denoted by $*** < 0.001$; $** < 0.01$; $* < 0.05$; $\dagger < 0.1$ or blank for no signficance.

(continued on next page)

Table 4.10 (continued). Multiple regression models of energy use per family per meal.

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.

4.5.2. 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 energy use for the entire village over any 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 4.11. Family size and the mass of meal ingredients explain a similar amount of variation in the test data obtained from cooking meals in Eqs. (4.22–4.25). 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. (4.23)), but differed if a researcher was not present near mealtime (Eq. (4.22)). 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. (4.22) has a higher correlation with family size, Eq. (4.23) 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 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. (4.26) does not perform as well as the regression on the mass of water in Eq. (4.27). The two regressions of energy use for roasting peanuts explained a similar amount of variation in test data, Eqs. (4.28) and (4.29). Energy use for making medicine and steeping tea are determined based on the rate at which a family makes medicine (Eq. (4.30)) and steeps tea (Eq. (4.31)). 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 (σ = 2.1, 3 obs.) and 25.6 MJ kg^{-1} rendered oil (σ = 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.

Equations (4.22–4.31) can be used to estimate daily household energy use for cookstove applications. The equations can be applied to each family in the village using Fig. 4.2 and then aggregated to calculate total village energy use. Two or more estimation methods are presented for cooking meals, heating water, and roasting peanuts. The diamonds differentiate between the equations using family size and the mass of ingredients cooked. Thus data gathering 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 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.

Table 4.11. Statistical models of energy use per family^{-1} day^{-1}.

Cookstove application	EQ	Estimators	Comments	Test type(s)
Cooking meals	4.22	$42.61^{*} + 6.56^{***} \times n_p$	regression, $R^2 = 0.8067$, 12 obs.	DCT
	4.23	$53.51^{**} + 3.90^{**} \times n_p$	regression, $R^2 = 0.7247$, 9 obs.	OCT, SCT
	4.24	$50.90^{**} + 2.01^{**} \times m_{tot}$	regression, $R^2 = 0.7662$, 9 obs.	OCT, SCT
	4.25	$31.60 + 10.83^{**} \times m_{dry}$	regression, $R^2 = 0.7281$, 9 obs.	OCT, SCT
Heating water	4.26	$9.70 + 2.64^{***} \times n_p$	regression, $R^2 = 0.6502$, 16 obs.	OCT, SCT, DCT
	4.27	$13.37^{*} + 0.43^{**} \times m_w$	regression, $R^2 = 0.8898$, 6 obs.	OCT, SCT
Roasting peanuts	4.28	$-0.911 + 0.446^{**} \times n_p$	regression, $R^2 = 0.8660$, 6 obs.	OCT, SCT
	4.29	$\left(9.92^{\dagger} + 4.21^{**} \times m_{pea}\right) \times r_{pea}$	regression, $R^2 = 0.8766$, 6 obs.	OCT, SCT
Making medicine	4.30	$18.3 \times r_{med}$	mean, $\sigma = 8.3$, 3 obs.	OCT
Steeping tea	4.31	$1.57 \times r_{tea}$	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}.

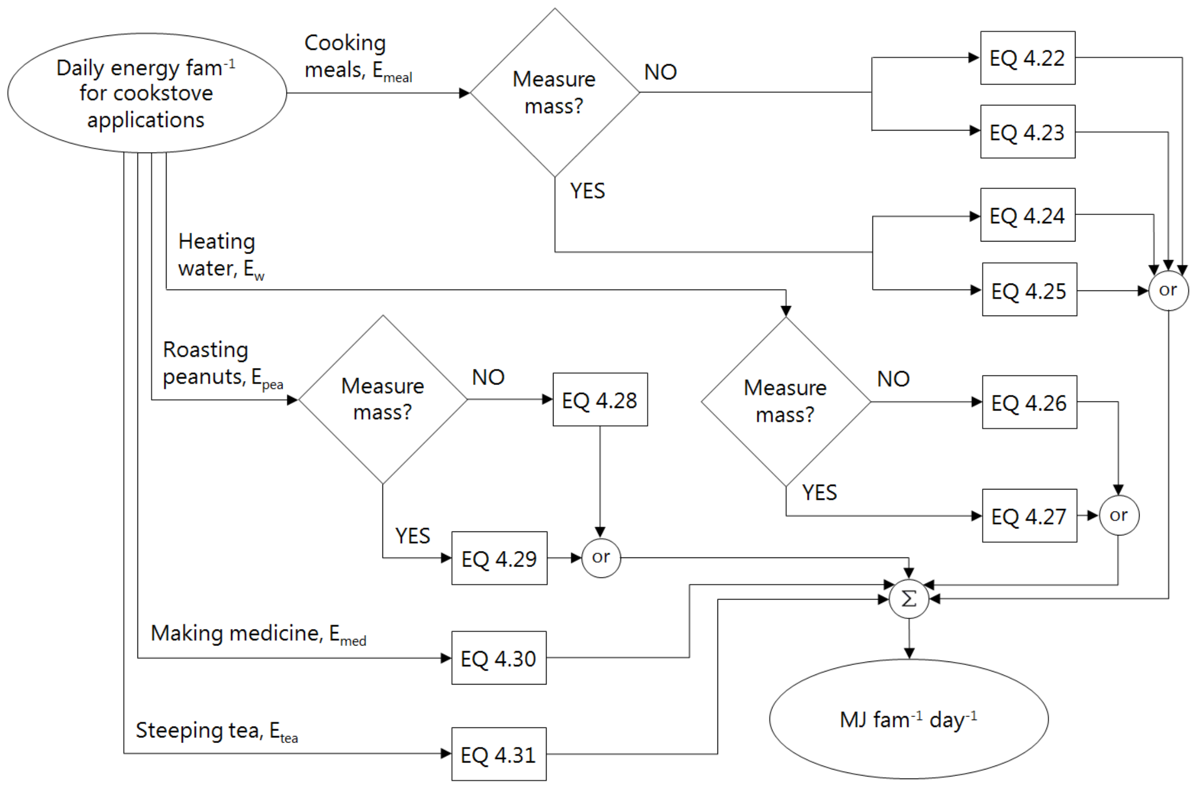

Figure 4.2. Estimation methodologies for daily household energy use for domestic cookstove applications. Shea processing not shown.

The total error in estimating daily household energy use can be represented as the weighted sum of errors across all cooking activities. First, the estimate error, err_i, is calculated for each cooking observation using Eq. (4.32). The observed energy use, E_i, is compared to the estimated energy use, $\hat{E}_i$, using the appropriate equations for each cooking activity (Eqs. (4.23), (4.26), (4.28), (4.30), and (4.31)). Table 4.12 provides the minimum, maximum, and average errors for each cooking activity. The weighted sum of these errors indicates that daily household energy use estimation 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 cooking meal and heating water energy use estimates.

$$err_i = \frac{\left|E_i - \hat{E}_i\right|}{E_i} \tag{4.32}$$

Table 4.12. Error in daily household cooking energy use estimation.

Cooking activities	Average error (range) (%)	Contribution to total energy use[a] (%)	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.

4.5.3. 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 charcoal 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 than on a meal basis, as indicated by the coefficient of variation of 0.31 on a daily basis and 0.54 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 ($p = 6.21\times10^{-5}$). Although total village energy use can be expressed in energy per capita, that statistic should be used with caution for estimating energy use, or in comparing energy use between families as is common in cookstove studies. 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. Therefore, wood consumption per capita should be used with caution when estimating total household or village energy use.

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 as the total energy use 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 meals 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, 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 cooking energy use, the DCT provides the least time-intensive method to measure fuel consumption, and subsequently 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 the qualitative factors affecting fuel consumption.

4.6. 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 being at 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 model of total 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 cooking energy use, those two applications could be used to approximate total cooking energy with minimal error. The total village cooking 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 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.

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 cooking energy use, estimate cooking energy use, or assess the impact of programmatic cooking 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 cooking energy use are needed from other world regions.

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CHAPTER 5

COMPARING ENERGY OPTIONS FOR DOMESTIC COOKING NEEDS IN A RURAL AGRICULTURAL VILLAGE IN THE SAHEL

A paper to be submitted to *Applied Energy*

Nathan G. Johnson, Kenneth M. Bryden

Abstract

Unmet energy needs are a hindrance to rural development and poverty reduction strategies in rural villages in many developing countries. Of these needs household cooking tasks such as preparing food and heating water often account for over 90% of village energy use. Wood is commonly the primary energy source. This paper examines the costs and expected benefits of various energy options for meeting domestic cooking needs of a rural agricultural village in southern Mali using field data on energy use and factors that influence technology adoption and effectiveness. Options considered include new types of cooking equipment such as improved stoves and solar water heaters and changes in cookstove use such as ignition methods and communal eating. Sixty programmatic options are created using various combinations of these energy options and compared using program cost and expected reduction in wood use. Annualized capital costs of options ranged from zero to US\$3,130 yr^{-1} for reductions in wood use between 10.0% and 86.8% of the 234 metric tons of annual domestic wood use for cooking. These ideal cases are analyzed further by considering the effect of technology adoption and use on wood reduction. Cookstove usage patterns with multiple cooking technologies suggest a single cookstove could easily displace 20% to 80%

less than the rated design performance, and that multiple cooking technologies or solar water heaters may be needed to achieve substantial reductions in wood use.

Key words

Rural energy, isolated village, sub-Saharan Africa, cookstoves, solar water heaters, wood savings, stove stacking

5.1. Introduction

There are many energy technologies that can reduce the effects of poverty in developing countries. Common examples include improved cookstoves that reduce wood consumption and time spent gathering wood, lighting that allows students to study at night and adults to run household businesses, and solar photovoltaic (PV) panels that power water supply systems. Although these benefits are well-recognized, developing countries are faced with challenges in providing basic energy services due to inadequate infrastructure, a lack of financial capital, and the global movement towards clean energy that fosters policies and financial mechanisms in favor of cleaner, and more expensive, energy options. Over the next 25 years, the energy demand of emerging economies is expected to increase by approximately two-thirds [Energy Information Administration 2011]. The majority of this demand growth will occur in urban centers. In contrast the basic energy needs of many isolated rural villages will remain unmet [International Energy Agency 2010]. And it is not clear which energy options developers and funders should invest time and money to get the most impact in rural villages. This article examines sixty combinations of energy options based on the expected costs and benefits for rural agricultural villages in the Sahel.

5.2. Background

In many villages household cooking tasks such as preparing food and heating water account for more than 90% of village energy use. Wood is commonly the sole source of energy for domestic cooking needs, and the primary source of village energy accounting for more than 90% of village energy supply in off-grid isolated rural villages [Johnson and Bryden 2012]. As a result the principal focus of many current rural energy interventions is reducing the impact of domestic wood use on human health and the environment [Bond and Sun 2005, Ramanathan and Carmichael 2008, Smith et al. 2011, Thompson et al. 2011]. Several laboratory and field studies have been completed to gather empirical data on the costs and benefits of cooking energy options [Asif and Muneer 2006, García-Frapolli et al. 2010, Partnership for Clean Indoor Air 2011, Nahar 2002, Pokharel 2004]. In a report reviewing multiple rural energy options Reddy et al. indicated that improved wood cookstoves were a near-term solution that offered the potential for immediate benefit. In contrast many other rural energy options require longer development and implementation time [Reddy et al. 2000]. In a review of household energy interventions and policies over the last 30 years, Bruce et al. reported that improved cookstoves have consistently been the most cost-effective alternative compared to other rural energy options [Bruce et al. 2011]. However, the wood savings attained with a cookstove intervention is reliant on local cookstove adoption rates and usage patterns in the implementation village. As of yet there has been little discussion during the design planning process on how these factors may affect program savings when implemented, even given the several studies that note the common behavior of users to "stack" or retain multiple cookstoves in operation [Davis 1998, Masera and Navia 1997, Miah et al. 2009, Pine et al. 2011, Ruiz-Mercado et al. 2011, Chapter 4 this thesis]. More analysis is needed of these effects during design planning and design selection to form a better understanding of expected option savings.

This study uses field data on energy usage and local factors that influence energy use and technology adoption to compare the cost effectiveness of programmatic energy options designed to reduce wood use. These options are focused on the need to reduce wood use for domestic cooking which constitutes three-quarters of all energy used in the study village. The reduction in wood use is considered to be a surrogate for reduced impact of domestic cooking on human health and the environment. Wood savings are evaluated in the ideal case of complete adoption and replacement, and then discounted using field data to form a more accurate picture of expected savings to aid in the design planning and design selection process. A unique feature to this study is that it compares the impact of providing new energy devices with the impact of changes in cookstove use. Providing new energy devices requires financial investment whereas operational changes in existing cookstove use need little financial investment. The effect of stove stacking and user adoption rates are discussed. Options are compared to determine the best investment for reducing wood consumption and the time spent gathering wood.

5.3. Village background

Approximately two-thirds of Mali's 13 million people live in rural areas [World Bank 2008]. 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 [Klugman 2010]. On a national level, biomass contributes to 78% of energy use [SIE-Mali 2007], and over 99% of households use solid fuels for domestic energy needs [World Health Organization 2003]. The national per capita energy use of 7,500 MJ cap^{-1} yr^{-1} is one-third of the average in Africa [SIE-Mali 2007].

This study examines energy options for an isolated rural agricultural village in Mali. All families live on subsistence agriculture. There is no access to the electrical grid and travel is by foot and bicycle on dirt roads. A market is accessible by a small bus that departs daily but is too far from the village to be accessible by foot or bicycle. 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$2,000, 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 built separate from the main living space. The village has sixty families with a total population of 770 people. Three seasons occur in the region: hot and dry (February to May); rainy and humid with moderate temperatures (June to October); and cool and dry (November to January).

This village was analyzed in to other studies that describe the overall village energy system dynamics and examined factors that influenced fuel consumption for cooking [Johnson and Bryden 2012, Chapter 4 this thesis]. This study uses the data and findings from these earlier studies to understand the types of energy options available for this village and their likely impact on village energy use. As shown in Fig. 5.1, wood is the primary energy source, providing 94% of village energy. Domestic needs contribute to 98% of village wood use. All domestic uses of wood are completed on cookstoves, except for space heating. The uses of wood in the home are cooking (52.2%), heating water (22.2%), space heating (19.1%), processing shea (2.7%), roasting peanuts (2.5%), and making medicine (1.3%). Domestic wood consumption for cookstove applications requires 234 metric tons of wood yr^{-1} for the village. Cooking meals and heating water constitute 64.5% and 27.4% of energy used on cookstoves, respectively, and a significant reduction in village wood use will require addressing one or both of these cookstove functions. Domestic energy expenditures amount to approximately US$100 fam^{-1} yr^{-1} for disposable batteries (65.2%), rechargeable batteries (22.5%), and kerosene (12.3%). Although there is no financial expense for wood, gathering wood is a significant time investment of 250 hrs cap^{-1} yr^{-1} and 40 hrs cap^{-1} yr^{-1} for women and children, respectively.

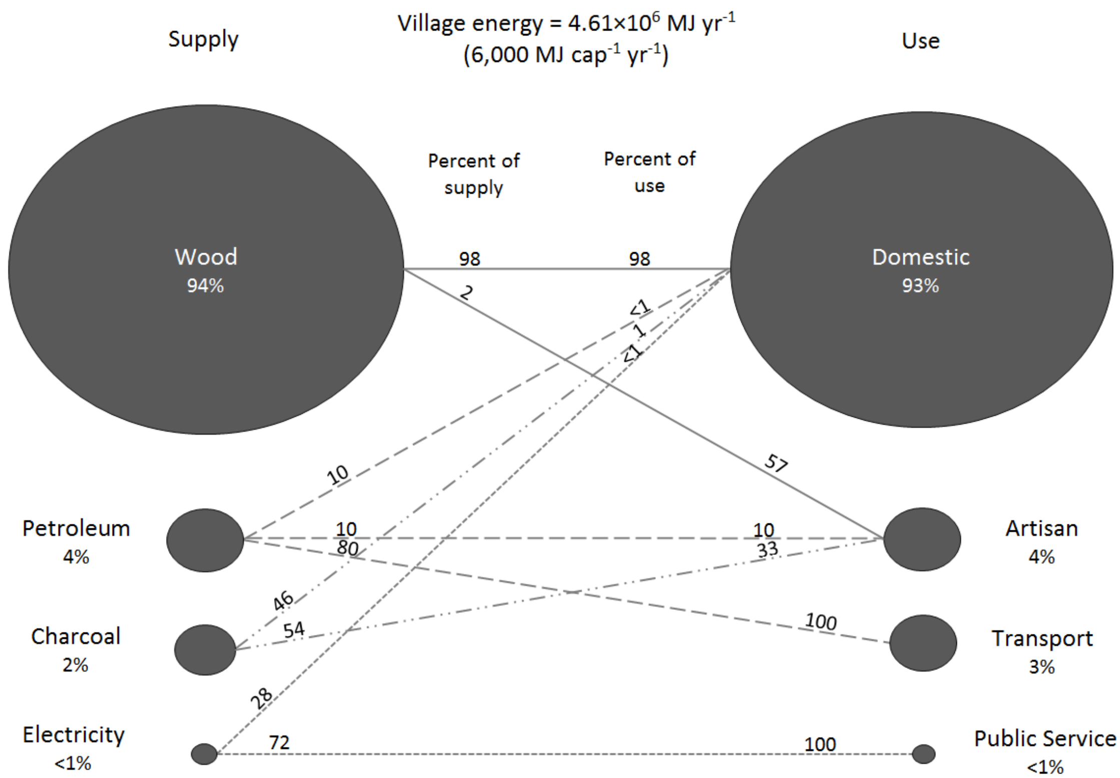

Figure 5.1. Village energy supply and use by percentage [Johnson and Bryden 2012].

Several factors impact the amount of energy used for cooking in the study village—the cookstove application, mass of ingredients prepared, family size, use of burning embers as an igniter, number of cooking fires, and to a lesser extent the type of cookstove.

Other findings of the earlier studies included:

- Increases in the mass of cooked ingredients were associated with a decrease in the amount of energy used per kg of prepared food. Family size, used as a proxy for meal size, has the same effect on cooking energy use. Thus preparing larger meals on fewer cooking fires can reduce total village wood consumption.

- The use of burning embers as an igniter was found to reduce the wood consumed for cooking a meal. For a meal of average size, burning embers reduce cooking energy use by approximately 10% after accounting for the energy in the char.
- One unexpected finding was that the improved cookstoves in the study showed no statistically significant reduction in wood use after accounting for other factors. Several factors may account for this such as local use behaviors, the small range of meal sizes cooked on the improved cookstove relative to the three-stone fire, and cookstove stacking. Noting that statistical validation of wood consumption savings requires a large number of field tests due to the highly variable operator effects this study assumes that cookstove fuel efficiency values representative of tests worldwide can be realized in this village.
- Cookstove stacking was prevalent. Approximately one-half of women owned more than one cookstove. In all cases of improved cookstove adoption the improved stoves were used as additional cooking appliances rather than replacements for traditional open fires.
- Shared cookstove ownership was common with 38.2% of women sharing a cookstove with one or two other women.

5.4. Setup of the study

There are several objectives associated with village energy projects. These include improved user health, preservation of the environment, reduced carbon emissions, and reduced work to gather fuel. A reduction in wood use for fuel can be used as a surrogate in evaluating option effectiveness at reaching these objectives and is therefore used as the figure of merit in this study. Interviews with subsistence-level agricultural families in the village strongly suggest that ready adoption by the user will be motivated by reduced work relative to the existing practices. The reduction in work to gather wood is linear with respect to wood use. While both carbon emissions and indoor air pollution are critical issues, there is limited data linking wood use to indoor air pollution due to many confounding factors, and carbon credits are a topic of financing that can be considered as an extension to this study. This study compares the annualized investment cost and wood use associated to each option and combinations of those options. The following assumptions are made to setup the study

1. Energy option capital is paid in full by a non-governmental organization (NGO) or governmental program, or financed such that it is affordable for a family (e.g., subsidized, micro-loan).
2. The programmatic costs associated with implementation and monitoring are born by the supporting external agency and not considered here.
3. The operating and maintenance costs (including fuel) are small relative to income.

Programmatic energy interventions to reduce fuelwood use for cooking include (1) improved cookstoves, (2) solar water heaters, (3) burning embers to ignite the fire, and (4) communal cooking groups. These options are compared to a base case for the village in which the 60 families, ranging in size from two to over 40 people, cook separately on traditional open fires. Currently, a total of 123 women use cooking stoves. Of this, 76 women cook separately and use their own cookstoves and the remaining women share 21 kitchens and cookstoves in groups of two or three women per kitchen, suggesting that the summation, 97, be considered for the quantity of cookstoves needed by a program to maintain current ownership and use patterns.

The cookstove options considered are

- Four common wood cookstoves listed in Table 5.1. The artisan improved cookstove is made in the district market by hand whereas the next generation single-pot describes machined cookstoves from an industrial process. The forced draft thermoelectric cookstove uses a fan to regulate airflow; the fan is powered by a thermoelectric module that converts a temperature differential between the interior and exterior cookstove walls into electrical power. The institutional cookstove is much larger than the other three stoves and is commonly used to prepare large meals.
- LPG and gas stoves. Using the cookstove efficiency values in [O'Sullivan and Barnes 2007] and the local price of kerosene and LPG in the study village, the annual fuel cost for using LPG and kerosene cookstoves would be approximately 7 to 11 times greater than current domestic energy expenditures. Further, there is no infrastructure to transport the quantity of fuel needed to displace wood use. Based on this LPG and gas stoves were not considered.
- Biogas. Using local data on waste availability and biogas production rates in [Nijaguna 2002, Subramanian et al. 1979] only 14% of the wood used for domestic cooking needs could be displaced by biogas.
- Solar cookstoves. These are not considered because for seven months of the year all meals are prepared outside of daylight hours. Breakfast begins before sunrise; lunch

is prepared shortly after sunrise to be brought to the fields in the farming season, or in the late morning; dinner is prepared late in the day after usable sunlight hours.

Table 5.1. Cookstove energy intervention options.

Cookstove	Lifetime (yr)	Capital cost (US$)[d]	Equivalent annual cost (US$ yr^{-1})[e]	Efficiency (%)
Artisan improved[a]	1.5	5.50	3.60	25
Next generation single-pot[a]	5	27.40	5.00	30
Forced draft thermoelectric[b]	5	95.20	17.20	30
Institutional[c]	10	250.00	19.90	50

[a]O'Sullivan and Barnes 2007.

[b]Kauw 2009.

[c]MacCarty 2010, Still 2011.

[d]Capital cost for one complete system. Initial cost and replacement cost are equivalent. It is assumed that each option has the same overhead cost for implementation. All costs are displayed in 2011 US$.

[e]Equivalent annual cost (EAC) is calculated using $EAC = C \times i \big/ \left[(1+i)^n - 1 \right]$, where C is the capital cost in US$, i is the discount rate at 5%, and n is option lifetime in years. Assumptions include no inflation rate and no salvage value.

Two solar water heaters with flat-plate collectors were considered and the costs averaged to form a representative solar water heater option. One conventional solar water heater with direct circulation in a close-coupled configuration was selected from South Africa at US$473 (exchange rate US$ 1 = South African Rand 8) [Cawood and Morris 2002], and an option from India using thermosyphon circulation with materials made from alternative low cost materials costing US$202 per unit (exchange rate US$1 = 50 Indian Rupees) [Nahar 2002]. Averaging these two solar water heaters a representative solar water heater with a cost of US$337 and a 15-year lifetime was assumed. The equivalent annual cost was $15.60. The solar water heaters have 100 L capacity and it is assumed this volume is used once per day. Field data of bathing water use in the study village indicates hot water usage to be approximately 10 L cap^{-1} day^{-1}. Based on this a total of 77 water heaters are required.

The effect of communal cooking and the use of burning embers are found using relationships from [Chapter 4 this thesis]. Cooking groups in the village range from 2 to 44 people per fire for a village-wide average energy use of 12.3 MJ $person^{-1}$ day^{-1} for cookstove applications. Switching to communal cooking groups of 40 or 100 people per fire would create a fuelwood savings of 27% or 35%, respectively, of the total wood consumption for cooking meals, heating water, and roasting peanuts. Wood use for shea processing is not related to family size, and medicine needs are typically met by individual families and not large cooking groups, therefore no reduction is expected for these activities if communal cooking is adopted. It is noted that communal cooking practices are a significant social change and may be viewed with hesitancy and negativity, but, communal cooking has been observed in other villages in the study region—a village six kilometers from the study village has groups that cook communally with up to 120 people per fire. Using burning embers to ignite the fire saves approximately 10% of wood used to cook a meal for an average family size. This reduction is assumed to occur for the other types of cookstoves considered here.

Table 5.2 summarizes the energy intervention options. The efficiencies of cookstoves are equated to percentage fuelwood savings using Eq. (5.1) for ease of comparison with other options

$$savings(\%) = 1 - \frac{\eta_b}{\eta_o} \tag{5.1}$$

where η_b is the efficiency of the base case (i.e., traditional three-stone fire at 15% [O'Sullivan and Barnes 2007]) and η_o is the efficiency of an alternative cookstove option.

Table 5.2. Energy intervention option fuelwood savings referenced to a traditional three-stone fire.

Options	Applicable cooking activities (% of wood use)	Savings (%)	Program EAC (US$)
Artisan improved cookstove	Meals, hot water, peanuts, shea, medicine (100.0)	40	350
Next generation single-pot cookstove	Meals, hot water, peanuts, shea, medicine (100.0)	50	490
Forced draft thermoelectric cookstove	Meals, hot water, peanuts, shea, medicine (100.0)	50	1690
Institutional cookstove	Meals, hot water, peanuts, shea, medicine (100.0)	70	1930
Solar water heater	Hot water (27.4)	100	1200
Burning ember igniter	Meals, hot water, peanuts, shea, medicine (100.0)	10	0
Communal cooking, 40 people	Meals, hot water, peanuts (95.0)	27	0
Communal cooking, 100 people	Meals, hot water, peanuts (95.0)	35	0

The following assumptions are used to simplify energy option comparisons

- Complete adoption and complete replacement—100% adoption of proposed energy option and 100% replacement of existing options used for the same cooking task(s).
- Time to collect wood per trip remains unchanged—Forest reserves are stable and are not affected by wood collection.
- Amount of wood collected per trip remains unchanged—Consumers do not reduce wood carried per trip if wood consumption changes, only the number of trips.
- End-use benefit does not change—Consumers do not change the end-use benefit from using a different energy option (e.g., food consumption does not change with different cookstove fuel efficiencies).

A central assumption in this study is 100% adoption of the intervention strategies and 100% replacement of existing cooking practices and technologies. This assumption defines an upper limit to the benefit that can be attained with an option.

Additional reductions in wood use can be attained by combining options. For example, combining the artisan improved cookstove with burning embers for ignition igniter results in a wood savings of 46% (40% + 10% × (100% − 40%)). Wood savings for options that do not affect all cooking activities are applied as a percentage of total cookstove wood use for the applicable cooking activities (e.g., 27.4% for heating water).

The error in cookstove option savings calculations is assumed to be 20% of potential savings, or approximately two standard deviations about the mean fuel use of improved cookstoves in [Jetter and Kariher 2009]. There is no error for solar water heating because no wood is used, and the errors of using burning ember for an igniter and communal cooking are 29.5% and 17.7%, respectively, as calculated from field data in Appendix L and Appendix O.

The four cookstoves, solar water heater, use of burning embers for igniting the fire, and two communal cooking group sizes can be combined in various permutations to form programmatic energy options. The flowchart given in Fig. 5.2 illustrates the process to create a combination. The permutations of all options can be combined into a hierarchical tree as shown in Fig. 5.3.

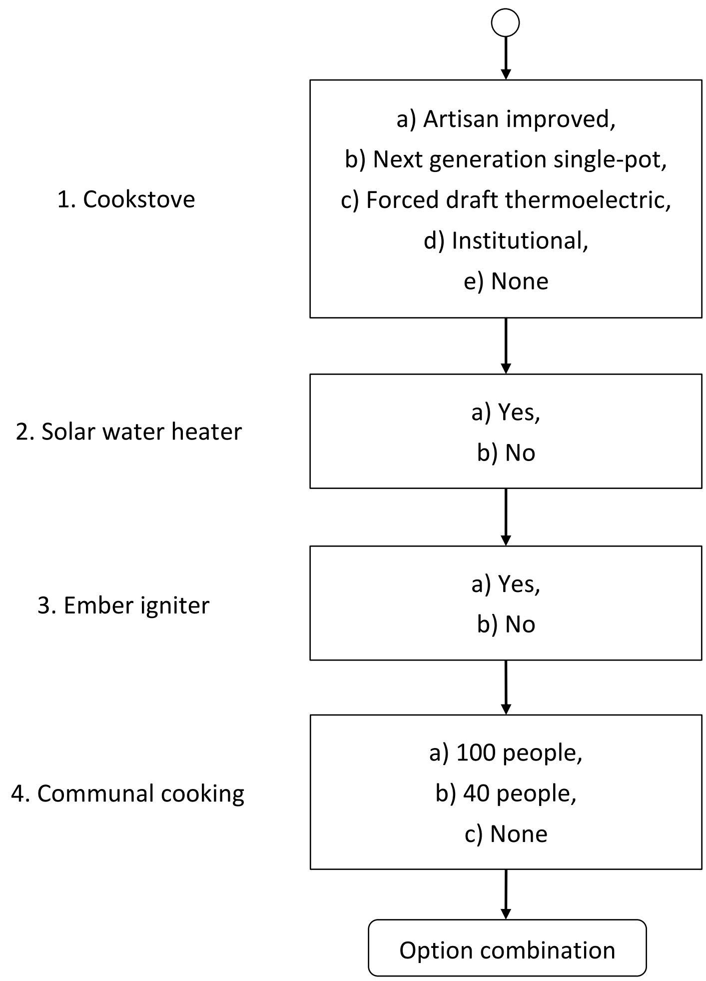

Figure 5.2. Flowchart for creating option combinations.

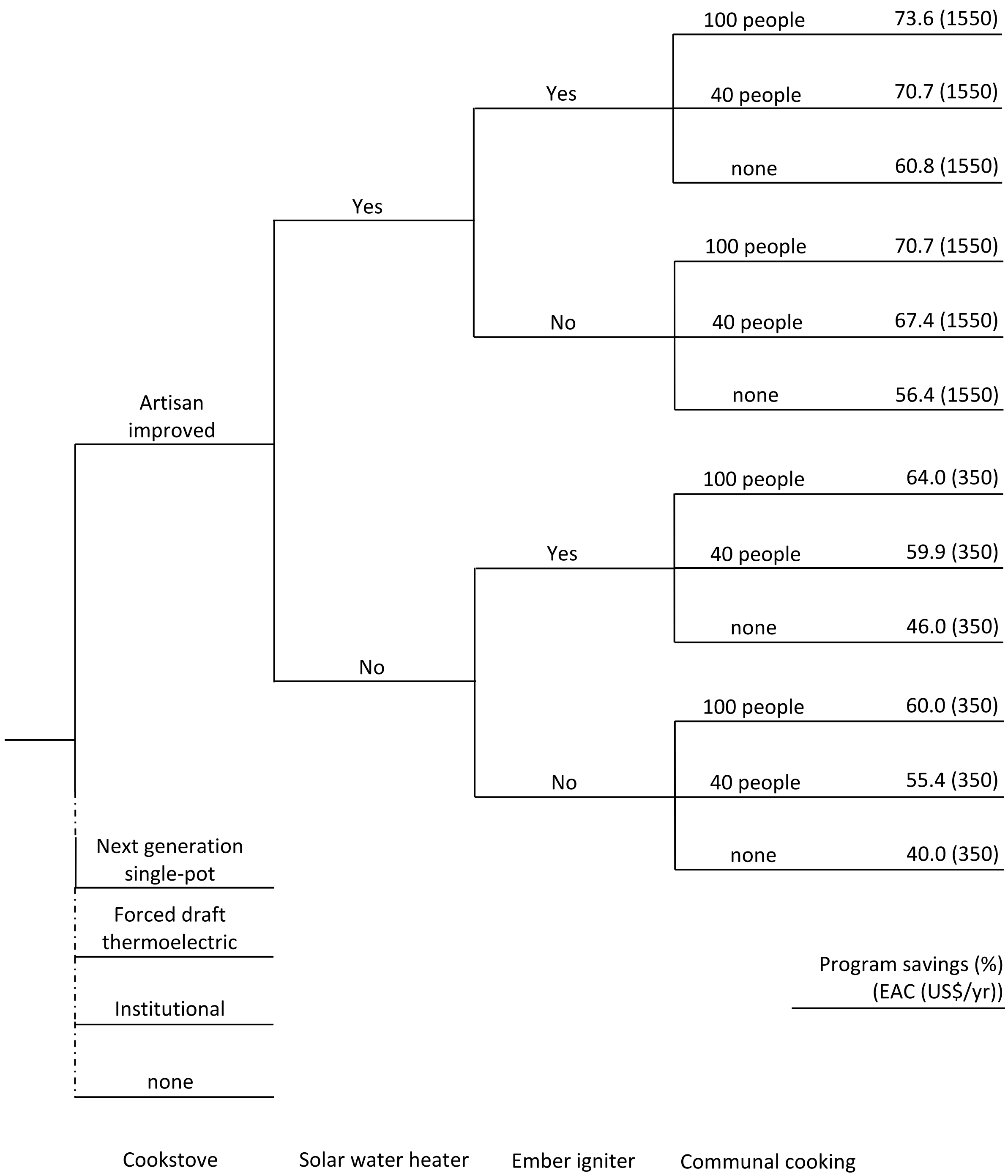

Figure 5.3. Energy option decision tree showing the subset of combinations that include the artisan improved cookstove.

5.5. Results

Fuelwood savings and annualized cost for the sixty programmatic energy options are given in Table 5.3 and graphed in Fig. 5.4. Program savings are given as a percentage of the base village case discussed earlier: wood consumption of 234 metric tons yr^{-1}, a time of 250 hrs cap^{-1} yr^{-1} for women gathering wood, and a time of 40 hrs cap^{-1} yr^{-1} for children gathering wood. In the ideal case of complete adoption and complete replacement a maximum savings of 86.8% can be expected for the combination including an institutional cookstove, a solar water heater, use of burning embers as an igniter, and communal cooking groups with 100 people per fire. This option would require an annualized investment cost of US$3,130. The maximum fuelwood savings expected with a combination including a solar water heater but excluding a cookstove is 56.1% for an annualized investment cost of US$1,200. It is worth noting that without any technological intervention, a savings of 40% could be reached if all families used burning embers for fire ignition and participated in communal cooking with 100 people per fire. Interestingly, this is the same fuelwood savings that would be expected from a program implementing an artisan improved cookstove, yet this technology would cost US$350 per annum whereas the changes in cooking behavior bear no capital cost.

Table 5.3. Wood savings and annualized capital cost of sixty combinations of energy options.

Cookstove	Solar water heater	Ember igniter	Communal cooking	Program savings (%) (EAC (US$/y))
Artisan improved	Yes	Yes	100 p.	73.6 (1550)
			40 p.	70.7 (1550)
			none	60.8 (1550)
		No	100 p.	70.7 (1550)
			40 p.	67.4 (1550)
			none	56.4 (1550)
	No	Yes	100 p.	64.0 (350)
			40 p.	59.9 (350)
			none	46.0 (350)
		No	100 p.	60.0 (350)
			40 p.	55.4 (350)
			none	40.0 (350)
Next generation single-pot	Yes	Yes	100 p.	78.0 (1690)
			40 p.	75.6 (1690)
			none	67.3 (1690)
		No	100 p.	75.6 (1690)
			40 p.	72.9 (1690)
			none	63.7 (1690)
	No	Yes	100 p.	70.0 (490)
			40 p.	66.6 (490)
			none	55.0 (490)
		No	100 p.	66.7 (490)
			40 p.	62.9 (490)
			none	50.0 (490)
Forced draft thermoelectric	Yes	Yes	100 p.	78.0 (2870)
			40 p.	75.6 (2870)
			none	67.3 (2870)
		No	100 p.	75.6 (2870)
			40 p.	72.9 (2870)
			none	63.7 (2870)
	No	Yes	100 p.	70.0 (1670)
			40 p.	66.6 (1670)
			none	55.0 (1670)
		No	100 p.	66.7 (1670)
			40 p.	62.9 (1670)
			none	50.0 (1670)
Institutional	Yes	Yes	100 p.	86.8 (3130)
			40 p.	85.4 (3130)
			none	80.4 (3130)
		No	100 p.	85.4 (3130)
			40 p.	83.7 (3130)
			none	78.2 (3130)
	No	Yes	100 p.	82.0 (1930)
			40 p.	79.9 (1930)
			none	73.0 (1930)
		No	100 p.	80.0 (1930)
			40 p.	77.7 (1930)
			none	70.0 (1930)
None	Yes	Yes	100 p.	56.1 (1200)
			40 p.	51.2 (1200)
			none	34.7 (1200)
		No	100 p.	51.2 (1200)
			40 p.	45.7 (1200)
			none	27.4 (1200)
	No	Yes	100 p.	40.0 (0)
			40 p.	33.2 (0)
			none	10.0 (0)
		No	100 p.	33.4 (0)
			40 p.	25.7 (0)
			none	0.0 (0)

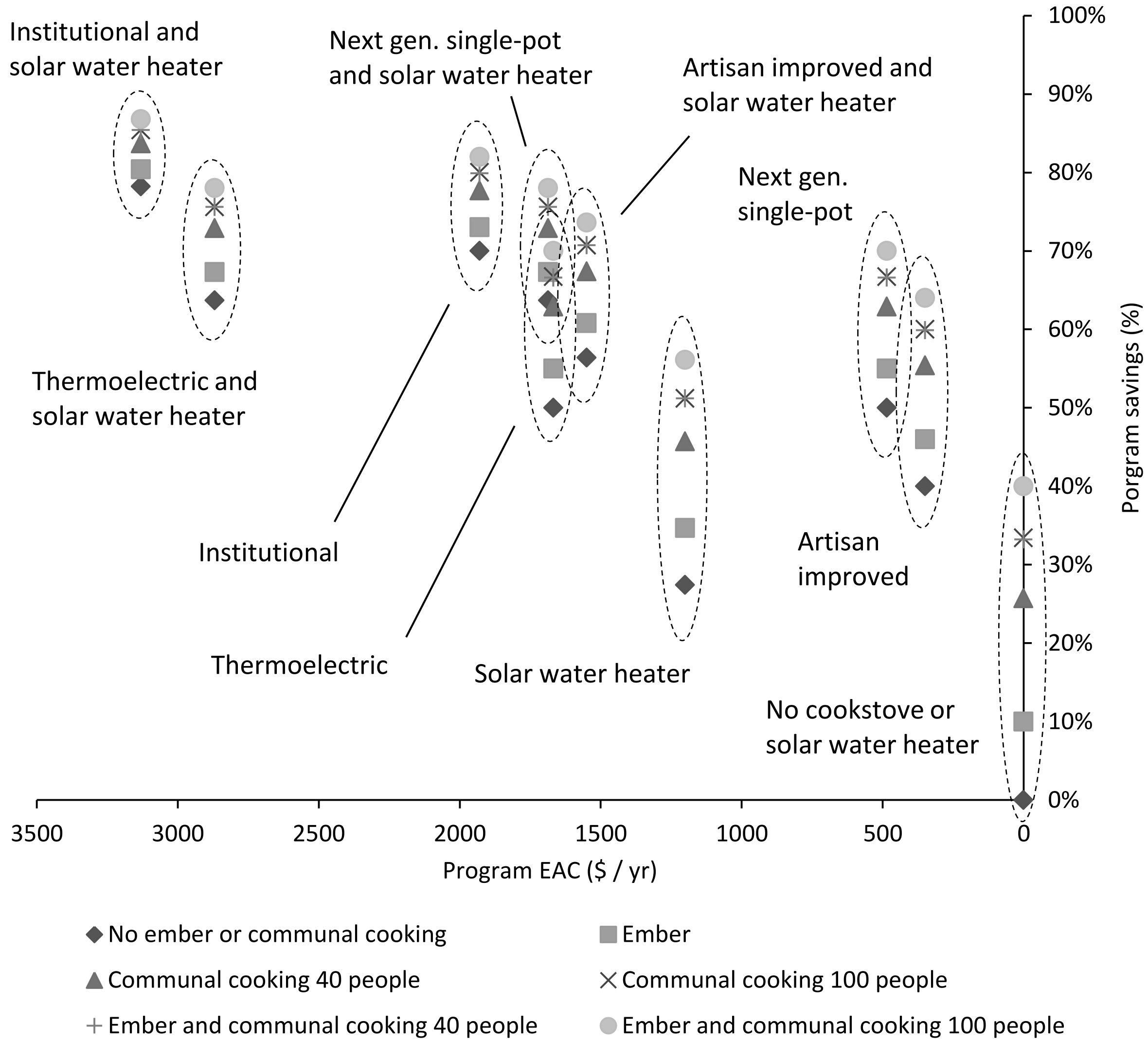

Figure 5.4. Annualized investment cost and program savings.

Wood savings of an implemented program is expected to be less than these idealized cases. The two primary causes of this discrepancy are 1) less than 100% adoption, and 2) stove stacking that results in less than 100% replacement. The effect of the adoption rate can be approximated a linear interpolation between complete rejection and complete adoption. Figure 5.5 shows the effect of the adoption rate on annual wood savings for each option.

Considering a scenario in which 50% of families adopt and use a new cookstove as their only cooking device (using data simplified from recent studies of improved cookstove adoption in Mexico [Pine et al. 2011, Ruiz-Mercado et al. 2011]), the comparative benefit to solar water heaters, assuming 100% adoption, is greatly decreased. The next generation single-pot cookstove and forced draft thermoelectric cookstove would have similar wood savings per year to that of the solar water heater option, and the artisan improved cookstove, a common intervention option, would underperform solar water heaters if cookstoves were adopted by only 50% of cooks upon implementation.

The effect of replacement rate is shown in Fig. 5.6 for the next generation single-pot cookstove. This example shows fuelwood savings if the cookstove is used for only one end-use (e.g., cooking meals) and if the cookstove is used only part of the time for that end-use (e.g., for breakfast and lunch but not dinner). Error bounds are calculated based on the estimate error in program savings given earlier. Considering a scenario in which 50% of cookstoves are adopted [Pine et al. 2011, Ruiz-Mercado et al. 2011] and, of those adopted, are used to replace smaller meal sizes associated to breakfast and lunch [Chapter 4 this thesis], the expected program savings would be closer to 10% ± 2% (shown as an X on Fig. 5.6) when using typical values for cookstove adoption and cookstove stacking. This value is significantly less than the rated cookstove fuelwood savings of 50%. The derated value is expected to more closely approximate the realized wood savings of a cookstove program rather than the idealized case of 100% adoption and 100% replacement which has not been observed in the study village or other villages in the region [Appendix K].

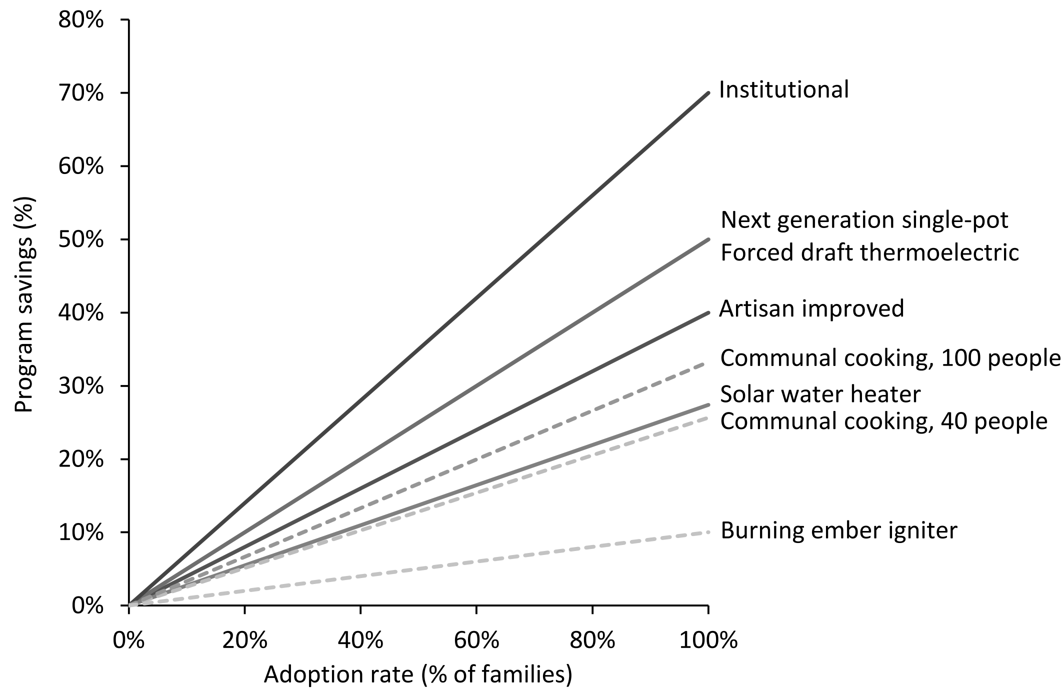

Figure 5.5. Effect of adoption rate on program savings of each option considered individually.

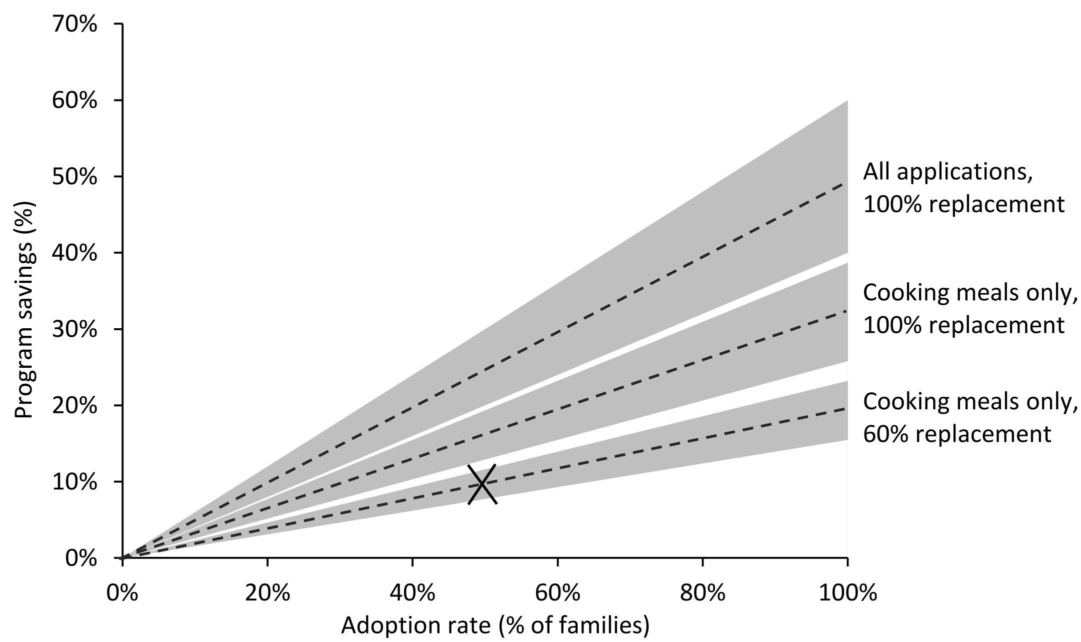

Figure 5.6. Effect of adoption rate, replacement rate, and savings estimation error on program savings for the next generation single-pot.

Note: Shaded regions represent ± 20% error in savings estimation. The “X” indicates 50% adoption.

Knowledge of cookstove usage characteristics in the village can provide further detail for estimating the impact of programmatic energy interventions. The fractional contribution shown in Fig. 5.7 is based on the family size, the number of families for each family size, and the energy use estimation equations introduced in [Chapter 4 this thesis]. The cumulative contribution to program savings is also shown. Approximately one-half of the maximum potential program savings could occur if a cookstove option was adopted by families of up to 15 people, or, adopted by families over 15 people in size. By using family size as an estimator for meal mass [Chapter 4 this thesis], this suggests that cookstoves with a capacity of up to 17 kg could realize one-half of program savings whereas a cookstove would need to be designed with a capacity of up to 50 kg to attain the remaining 50% of potential program savings. Data from improved cookstove adoption and stacking in the village illustrates that improved cookstoves are not used for this higher range in meal mass, used sparingly for breakfast meals of low mass, and occasionally to frequently for cooking small pots of sauce while the grain component to the meal is prepared on a traditional three-stone fire. This information suggests that similar cookstove designs would achieve no more than 50% of the rated savings for cooking meals, and likely, much less than this figure due to stove stacking, even at smaller meal sizes.

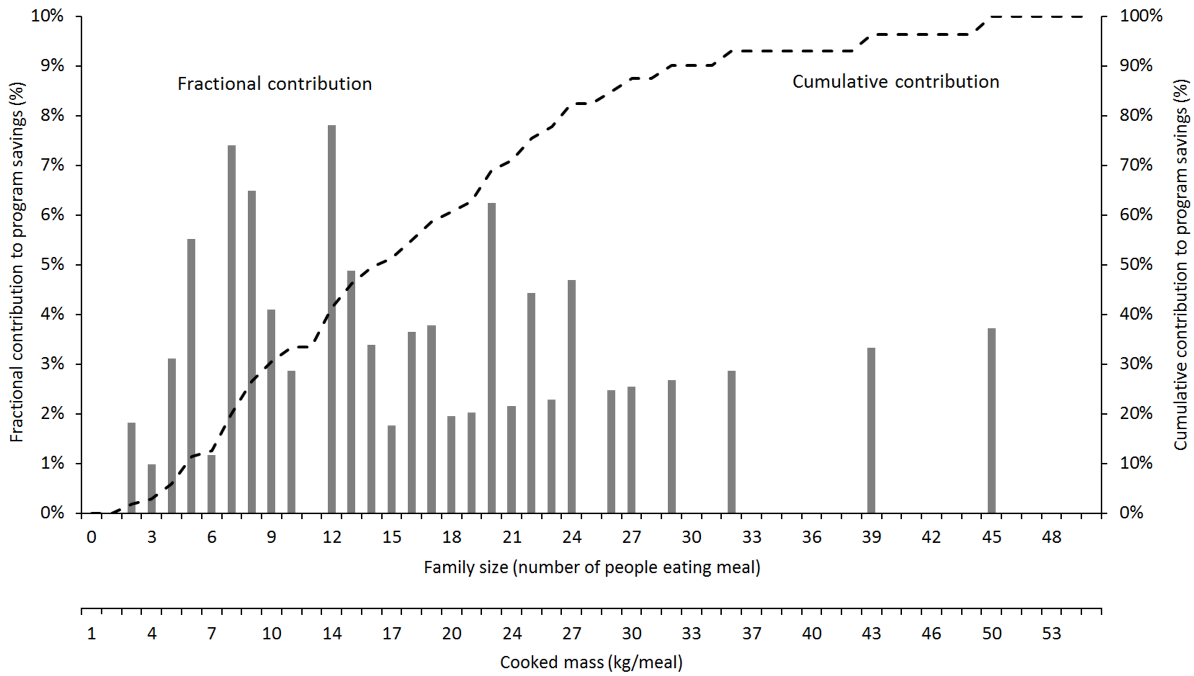

Figure 5.7. Fractional and cumulative contributions to fuelwood savings based on family size and meal mass for a cookstove option used to cook meals.

5.5.1. Discussion of results

Fuelwood savings from the sixty combinations of energy options range from 10.0% to 86.8%, with annual financial investment of zero dollars up to US$3,130. Savings of up to 40% could be possible with no capital cost required if programs encourage the use of burning embers to ignite fires and communal cooking groups of 100 people. Communal cooking practices have been observed in surrounding villages but more discussion is needed with the study village to determine if families would accept this option. Communal cooking has the three-fold benefit of reducing wood use, reducing time spent collecting wood, and reducing the frequency each woman cooks because there is a larger group of people taking turns to prepare meals and hot water.

Fuelwood savings above 40% require financial investment in the cookstoves and solar water heater options presented in this study. The long lifetimes for the institutional cookstove and solar water heater make them attractive one-time investments that do not require additional funding in future years. However, partial adoption of an energy option and cookstove stacking will decrease fuelwood savings below the savings associated to the ideal case of complete adoption and complete replacement. Since approximately one-half of women own more than one cookstove, and use each of the stoves, it is unlikely that any single cookstove option will replace the three-stone fire. Common literature figures and local data on improved cookstove adoption rates and cookstove stacking were shown to feasibly reduce the realized fuelwood savings of a cookstove option to only 20% of rated savings associated to the technology.

5.6. Conclusions and future work

This study compared sixty combinations of energy options using four cookstoves, a solar water heater, burning embers for fire ignition, and two sizes of communal cooking groups. The maximum potential impact of each option was calculated assuming complete adoption and use. However, cookstove stacking is common in the village and that practice reduces the cost-effectiveness of an option relative to the ideal case of complete adoption and use. This user preference is expected to continue given that the improved cookstoves currently in the village are considered as supplementary technologies to the traditional three-stone fire, and, only used for smaller meals cooked by less than half of the village. The efficacy of new cooking technologies can be considered by comparing the expected effectiveness across a range of meal sizes and family sizes. Solar water heaters may provide comparable or greater reductions in wood use due to high adoption rates for the technology that provides consistent performance and is easy to use. Behavioral changes in cookstove use that included communal cooking and using burning embers to start the fire showed the lowest potential reduction in wood use, however, the options require no capital cost and may be readily adopted. Implementing these changes may include changes to cooking culture, social habits, and local economies. As such, collaboration with social scientists such as anthropologists, sociologists, and economists would be helpful to understand the broader implications of each option.

The cookstove usage rates discussed in this study represent an initial understanding of the effect of cookstove adoption and cookstove stacking on rural energy option impact. Adjusting the potential fuelwood savings of an idealized case with local data on cookstove adoption and cookstove stacking is a topic for further research. Understanding local cookstove usage rates can indicate technological and programmatic design needs, and provide a more accurate depiction of fuelwood savings upon implementation. Studies of adoption and use of other technologies in rural energy interventions are also needed. This research can be extended to include other metrics such as emissions and user health.

Acknowledgements

The authors would like to thank Lanceni Keita and the late Dr. Steve DeVore for their support of these studies.

CHAPTER 6

CONCLUSIONS AND FUTURE RESEARCH

This thesis presented the tools and data used for understanding energy system dynamics for an isolated rural agricultural village in West Africa. The human, natural, and engineered factors that influence village energy supply and use were identified and described using quantitative and narrative data. Methods and findings from the research were presented in three parts: (1) the overall dynamics of village energy supply and use for a one-year period, (2) the factors that influence fuel use for domestic cookstove applications, and (3) an assessment of the costs and benefits of various energy options for meeting domestic cooking needs.

Annual village energy use for the village was 6,000 MJ cap^{-1} yr^{-1}. Wood is the primary energy source, providing 94% of village energy. Approximately 98% of this wood is used to meet domestic energy needs at 375 kg cap^{-1} yr^{-1}, or approximately 1 kg cap^{-1} day^{-1}. Domestic wood consumption in the village is in the lower quartile of other rural energy studies completed in sub-Saharan Africa ranging from 110 to 1630 kg cap^{-1} yr^{-1}. Seasonal variations in energy used were found for domestic (260%), artisan (350%), and transport (210%) energy use sectors whereas public service energy use showed no seasonal dependency. Domestic wood consumption reached a minimum of 0.79 kg cap^{-1} day^{-1} in the hot season and a maximum of 2.41 kg cap^{-1} day^{-1} in the cold season due to energy use for space heating. Domestic use of charcoal—for making tea—showed a similar seasonal variation whereas the use of kerosene and electricity for lighting showed minimal seasonal change. Every household uses multiple energy sources to meet basic needs, providing supporting evidence of the "fuel stacking" hypothesis for rural villages. Families pay a premium for energy in both time and money. Gathering wood is a significant time investment of 250 hrs cap^{-1} yr^{-1} and 40 hrs cap^{-1} yr^{-1} for women and children, respectively, and total domestic expenditures on energy amount to US$1.88 fam^{-1} $week^{-1}$. Disposable batteries account for 65% of these expenditures. Although the share of village energy attributed to disposable batteries is negligible, the financial expense and waste generated from the 21,000 batteries used each year is significant. The largest and smallest energy sources in the village, wood and electricity, respectively, provide vital functions—cooked meals, hot water, warmth, clean water, lighting, and power for small electronics.

Fuel use for domestic cooking applications contributes to three-quarters of all village energy use. Survey findings described the ownership and use of the five wood cookstoves available in the village. In regards to cookstove ownership, the three-stone fire was the most prevalent in the village at 98.4% ownership rate among cooks, and it was the only cookstove used for all cooking tasks using fuelwood—cooking meals, heating water, processing shea, roasting peanuts, making medicine. Although the three-stone fire is widely used, approximately one-half of cooks own more than one cookstove, suggesting evidence of "stove stacking" in which a cook uses more than one technology to address cooking needs. The two traditional cookstoves served as the primary cookstove for all families whereas the three improved cookstoves were used as a supplement for cooking breakfast porridge, cooking sauce, or heating small quantities of water for bathing; a small metal charcoal cookstove was used only for steeping tea. Although all meals observed in the village were variants of six basic meal types, the dry ingredient mass as a percent of total meal mass varied by up to nearly three-fold between similar meal types, suggesting that the data recorded in common cookstove comparison studies (i.e., meal type and total meal mass) may not provide enough information to describe the factors that affect energy use for cooking. This and other factors were examined using three household cooking tests developed to directly examine energy use for cooking. Results from multiple regression analysis of energy use for cooking meals indicated 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 (Observational Cooking Test or Session Cooking Test).

Cooking energy use was also analyzed on a per day basis. Simple linear regression analysis was performed on energy use for cooking meals, roasting peanuts, and heating water. When possible, multiple equations were given to estimate energy use. These equations were combined in a decision diagram to aid in selecting methods to estimate daily household fuel consumption for cooking. Applying this methodology to all families and aggregating the result provides the total village domestic energy use for cooking. The cooking test and estimation methodologies can be used to design several types of rural energy studies based on the objective, desired accuracy, financial and personnel resources, and time available for the study. In considering possible research objectives, studies seeking to measure or estimate energy use can be completed for the least time and cost using the Daily Cooking Test. But studies seeking to inform decisions on programmatic cooking interventions should utilize the Observational Cooking Test and Session Cooking Test to obtain detailed data on each cooking session for use in describing multiple opportunities to reduce fuel consumption. Additionally, the Observational Cooking Test involves direct observation of the cooking activity and can be used to describe the qualitative factors affecting fuel consumption that are often pertinent when designing programmatic interventions.

The final component to the thesis compares energy options because it is not yet clear which village energy options developers and funders should invest time and money to provide the most benefit to human health and the environment. Options considered include new types of cooking equipment such as improved stoves and solar water heaters and changes in cookstove use such as ignition methods and communal eating. Sixty programmatic options were created using various combinations of these energy options and compared using annualized investment cost and expected reduction in wood use. Fuelwood savings from the sixty combinations of energy options ranged from 10.0% to 86.8% with an annual financial investment of zero to US$3,130. Savings of up to 40% could be possible at no capital cost if programs encourage the use of burning embers to ignite fires and communal cooking groups of 100 people. Fuelwood savings above 40% require financial investment for the cookstoves and solar water heater options presented. The long product lifetimes of the institutional cookstove and solar water heater make them attractive one-time investments that do not require additional funding in future years. However, partial adoption of an energy option and cookstove stacking will decrease fuelwood savings below the savings associated to the ideal case of complete adoption and complete replacement. Since approximately one-half of women own more than one cookstove, and use each of the stoves, it is unlikely that any single cookstove option will replace the three-stone fire. Common literature figures and local data on improved cookstove adoption rates and cookstove stacking were shown to feasibly reduce the realized fuelwood savings of a cookstove option to only 20% of the rated savings associated to the technology.

The methods and data presented in this study seek to describe energy flows in an isolated rural agricultural village. Additional studies are needed in the Sahel to gather more empirical data and confirm factors that are significant to explaining village energy use. Studies are also needed in other world regions to contrast the effects of different human, natural, and engineered systems on energy flow in society. These studies in multiple world regions and in communities with varying degrees of development will generate further data and insights to inform decisions for sustainable engineering and engineering for development. To this end the following work is needed

- More comprehensive investigation of the effect of cookstove adoption and cookstove stacking on program fuelwood savings;
- A comparative assessment of cookstove performance tests and cooking energy tests introduced in this thesis—when to use them and why;
- Identification of the human, natural, and engineered system factors that affect the implemented program benefits of all rural energy options;
- Longitudinal studies completed before and after an energy intervention to study changes in village systems (e.g., use of technology, human health, resource availability, wealth and commerce, educational attainment, gender differences);

- Research to understand the differences in energy system dynamics and energy needs between rural villages and peri-urban areas;
- A methodology for the engineering design of rural energy alternatives that incorporates procedures and insights from this thesis.

The long-term objective of this work is to develop the understanding and tools needed to design and implement sustainable energy solutions for rural villages. This work requires an integrated analysis of the dynamic human, natural, and engineered systems that affect energy flow in society. Findings will guide engineering research towards energy options that can provide the most benefit to human health and the environment, and bracket the design space for technical and programmatic design decisions to achieve long-term sustainability and development.

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APPENDIX A

SUMMARIZED PROGRAMMATIC AND TECHNICAL DESIGN GUIDELINES

Table A.1. Summarized programmatic design guidelines.

General
1. The family is the central socio-economic unit in the village. As such, it is often easier to implement and test projects with families rather than higher socio-economic levels (e.g., the village) which require consensus and coordinated financial investment of multiple parties that often have little disposable income to spend outside of their immediate family needs. 2. Understanding rural energy needs is an exploratory process of questioning that begins with surveying the village, follows with qualitative research and participant observation, continues with focused quantitative research and testing, and follows with an initial set of project options to discuss with the village to establish the needs and objectives of the selected design. 3. Field visits lasting for more than one week and repeated visits are encouraged to build a relationship and trust with village leadership and families to speak openly about village needs and preferences, as well as introduce funder capabilities and interests. 4. Repetitive visits show different viewpoints of village needs based on the time of year, which, as suggested by this study, seasons is a significantly impacts village energy dynamics.
Economics
1. Observations of energy options implemented in the village suggest that users provide critical advice when they must pay for the products rather than receiving items for free. 2. The operation and maintenance costs (including fuel) of a new technology must be small relative to income to be a viable alternative to current energy use patterns and technologies. 3. Technology payment plans that favor the rental of capital intensive options rather than full purchase have shown promise in providing financial sustainability for both the business owner and the rental customer. Especially when the customer does not bear the financial risk of product failure by opting into a warranty system.

Table A.2. Summarized technical design guidelines.

General
1. Interviews in the village strongly suggest that technology adoption by the user is motivated by reduced work relative to existing practices. 2. Approximately 10% of the village migrates outside of the village for farming. Viable options that provide year-round benefits to these families would need to be portable, or, be implemented in both the village and the hamlet next to farming plots. 3. Solar panels for water pumping often exceed the power output needed to supply village water. The excess energy could be used to supplement battery charging or other power needs. 4. Villagers express interest in durability to protect their financial investments in new products, or prefer a warranty program to mitigate the risk of product failure. 5. With limited access to markets, technology repair and routine technology maintenance must be capable of being completed by local artisans using local materials and tools.

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Table A.2. (continued) Summarized technical design guidelines.

Domestic cooking
1. Wood and charcoal are the only viable fuels in the short term. a. Electricity infrastructure is not sufficient to meet the capacity or demand of power for cooking. b. Petroleum fuel expenditures for cooking would be 7 to 11 times greater than current domestic energy expenditures. This is prohibitively expensive. Further, there is no infrastructure to transport the quantity of fuel needed to displace wood use. c. Biogas can only supply a limited amount of domestic cooking needs—14% of current wood use. d. Solar cookers would require substantial changes in meal times, eating practices, and work schedules due to agrarian living. Seven months of the year all meals are prepared outside of daylight hours. Breakfast begins before sunrise; lunch is prepared shortly after sunrise to be brought to the fields in the farming season, or in the late morning; dinner is prepared late in the day after usable sunlight hours. e. It is unlikely meals will be prepared in the fields when farming due to the burden of transporting ingredients and cooking equipment—there is no place to leave possessions securely overnight in the field. 2. Many cooks retain multiple types of cooking devices, suggesting that a single improved cooking device is insufficient to address the wide range of cookstove applications. a. The three-stone fire is the only cookstove used for all cookstove applications. b. Cooks use different three-stone fires for cooking meals, heating water, and roasting peanuts. The three stones are spaced differently for each application. c. No improved cooking device in the village replaces all cookstove applications of the three-stone fire. d. Improved cookstoves are used primarily for cooking breakfast meals, cooking the sauce for lunch and dinner, or heating small quantities of water for bathing. e. On average, three cookstoves are owned per cook (365 cookstoves, 123 cooks). This is approximately one cookstove for every two people in the village of any age and gender (365 cookstoves, 770 people). 3. Peanuts are roasted over a fire by tilting the pot at an angle to concentrate peanuts in a smaller region within the pot. An improved cookstove should be capable of holding pots at a tilt to displace the use of a three-stone fire for roasting peanuts. An alternative option would be a specialized cooking vessel to roast peanuts on the existing improved cookstoves in the village. 4. Many women would like a hand-crafted metal cookstove fabricated in Mali, yet the delivered cost of US$10 seems to prevent purchase. As such, this value could be considered as an approximate price ceiling for the one-half of the women in the village who own no improved cooking devices. 5. Women do not like to cook in the sun and prefer to cook meals inside a kitchen for most of the year; women cook outside during extremely warm days (+45 °C) in the summer months. Hot water is commonly prepared outside because it is easier for family members to approach the stove instead of inside a small kitchen. Since the pot size and heated mass is much larger with water heating than with meals it can be expected that outdoor cooking devices will need to be more durable than indoor cooking devices to accommodate the larger pot size and mass. 6. Kitchens are made from wattle and daub. This construction is susceptible to failure from heavy seasonal rains. Several kitchens collapse completely or lose sections of walls each year in the village. Cookstoves built within kitchens may be lost when kitchens collapse.

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Table A.2. (continued) Summarized technical design guidelines.

Domestic cooking (continued)
7. Women commonly complete several tasks in parallel with cooking a meal (e.g., tending children, collecting water, preparing vegetables for the meal) and may be away from the fire for up to 15 minutes. A cookstove that can maintain a stable fire over this interval without being tended could lead to faster cooking and a reduction in products of incomplete combustion by avoiding a smoldering fire. 8. The temperature of water heated for bathing ranged from 39 to 48°C, with an average of 43.7°C and standard deviation of 2.8°C. A solar water heater should be capable of reaching the high temperature range. A cold water outlet attached to the solar water heater could be a useful addition that allows users to mix water to the appropriate temperature without need for additional water retrieval. 9. The maximum mass observed on a cookstove can indicate structural constraints or consumer viewpoints on stove stability. This mass is 45 kg for the three-stone fire, 18 kg for the gakourouwana, 6 kg for the low thermal capacity, 18 kg for the hand-crafted metal, and 9 kg for the manufactured metal stove. 10. Cooking firepower ranged from 2.1 kW to 13.8 kW for cooking meals on a three-stone fire. Assuming the three-stone fire is 15% efficient, a new stove design would need to provide 0.3 kW to 2.1 kW of heat into the pot for cooking meals.
Shea processing
1. The shea kernel is first heated to soften the meat by (1) boiling over several hours, (2) smoking the kernels in an oven over several days. Fires need to be tended regularly during this period and often go out, increasing the time needed to process shea by as much as a factor of two. 2. Given that technology adoption is heavily influenced by a reduction in work, a solar drier is an option to consider that benefits users by circumventing the need to tend the fire or oven. Further, reduced wood use and reduced deforestation is an interest of many external funders.
Space heating
1. Space heating accounts for approximately one-fifth of domestic wood use. Improved heating stoves could be considered as an option to reduce this amount. Indoor heating stoves with a chimney could significantly reduce the indoor air pollution compared to the current practice of open indoor heating fires with little air exchange between the enclosed space and outdoors. 2. Deaths have occurred in the village if a fire goes out during a night in the cold season. This especially affects the elderly, and often the elderly keep fires burning all day inside their home. Some villagers expressed their belief that smoke from indoor fires could lead to illness and death among the elderly.
Transportation
1. Limited motorized transportation occurs in the village even though several families own a motorcycle. Gasoline fuel purchases double when villagers have disposable income in the months following harvest. This suggests that fuel price is a limiting factor on mobility and alternative fuels or transportation methods could be viable projects.
Artisan energy use
1. The baking oven has a large thermal mass that requires a large amount of wood relative to the number of loafs produced. A smaller more efficient oven may allow the baker to make bread more often using less wood, or at a lower cost, allowing the baker's business to benefit and the villagers to benefit by more days with fresh bread.

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Table A.2. (continued) Summarized technical design guidelines.

Ambient lighting
1. The payment rates for battery and light fixture rental (US$2.00 per month to rent, US$0.50 to charge) are within the means of families in the village and are acceptable prices for the quality of light compared to the cost and quality of kerosene lanterns. a. Domestic use of kerosene for lighting has decreased by approximately one-half since initiation of the battery and light rental program. b. There is a waiting list to join the battery and light rental program. c. Lead-acid batteries provide additional benefits. They are also used for charging cell phones and powering radios. 2. Ambient lighting is common in the nighttime for socializing, and to a lesser extent, studying. The use of linear fluorescent bulbs powered by lead-acid batteries is rare in the morning. 3. Ambient lighting is used for safety for seeing snakes in the home.
Flashlights and portable lighting
1. Flashlights are primarily used during the early part of the day by women cooking breakfast and by children walking to school to a nearby village before sunup. 2. Flashlights are used at night to help identify paths in the village that are not illuminated by ambient lighting. 3. A portable source of lighting is used for safety to help see snakes along the path, in the kitchen, or in the home. 4. A total of 21,000 disposable batteries are used and discarded in the village each year. The batteries constitute 65% of all domestic energy expenditures. This expense and environmental hazard is a good indication that small rechargeable batteries or other renewable and portable source of lighting would be an attractive rural energy option to villages and external funders.

APPENDIX B

DEMOGRAPHIC SURVEY

Date		Head male		Family ID	
Location		Religion		Ethnic group	

No	Name	Relation to family	In NK? (Y/N)	M/F	Age (yr)	Occupation	Income (CFA)
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							
26							
27							

Table B.1. Demographic survey data.

Family ID	Number of people[a] Child	Adult female	Adult male	Elder	Total	Std. adult equiv.[b]
F01*†	15	2	2	3	22	13.5
F02	3	1	1	0	5	3.3
F03	12	4	1	3	20	12.6
F04	11	3	3	0	17	10.9
F05	12	5	3	0	20	13.0
F06†	6	3	1	3	13	8.8
F07†	9	1	1	2	13	7.9
F08	8	3	1	1	13	8.2
F09‡	3	3	1	0	7	4.9
F10	15	4	3	1	23	14.5
F11	32	6	4	2	44	26.4
F12†	11	4	2	0	17	10.7
F13*	8	3	3	0	14	9.4
F14	5	2	2	1	10	6.9
F15	26	7	6	2	41	26.2
F16	6	3	1	3	13	8.8
F17‡	7	1	1	0	9	5.3
F18†	5	1	1	0	7	4.3
F19‡	6	2	1	0	9	5.6
F20	21	4	4	0	29	17.7
F21	2	2	1	0	5	3.6
F22	1	2	1	2	6	4.7
F23	5	1	1	2	9	5.9
F24	14	3	1	3	21	12.8
F25	10	2	1	0	13	7.6
F26	19	2	4	2	27	16.7
F27	6	2	2	2	12	8.2
F28	4	1	1	1	7	4.6
F29	14	3	3	2	22	14.0
F30	3	1	1	0	5	3.3
F31	2	1	1	0	4	2.8
F32	6	1	1	0	8	4.8
F33	9	2	1	0	12	7.1
F34	5	1	1	0	7	4.3
F35	5	2	2	0	9	6.1
F36	1	1	1	0	3	2.3

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Table B.1. (continued) Demographic survey data.

Family ID	Number of people[a]					Std. adult equiv.[b]
	Child	Adult female	Adult male	Elder	Total	
F37	6	1	1	0	8	4.8
F38†	11	2	1	1	15	8.9
F39*	18	3	3	2	26	16.0
F40	6	1	1	0	8	4.8
F41†	12	3	3	0	18	11.4
F42	8	4	4	3	19	13.6
F43	9	2	3	0	14	9.1
F44	19	5	2	0	26	15.5
F45	0	0	0	2	2	1.6
F46	13	3	0	0	16	8.9
F47	3	1	1	0	5	3.3
F48	17	3	3	1	24	14.7
F49	0	1	2	1	4	3.6
F50*	6	3	3	0	12	8.4
F51	3	1	1	0	5	3.3
F52	2	1	1	0	4	2.8
F53	1	0	0	1	2	1.3
F54	9	3	3	1	16	10.7
F55†	22	6	4	0	32	19.8
F56	5	1	1	0	7	4.3
F57†	5	1	1	1	8	5.1
F58*	15	3	2	0	20	11.9
F59*	7	2	1	0	10	6.1
F60*	6	1	1	0	8	4.8
Totals	530	140	107	48	825	522.4

*Some or all of family leaves the village during farming season, June through January, to live in hamlets.
†Family size includes visiting students from October through June which attend primary school in study village.
‡Part of family attends school or works in the capital, Bamako, and returns to the one to three months per year.

[a]Maximum family size during the year. Children 0-14 years; adult women 14-59 years; adult men 14-59 years, elders 59 years and above.
[b]Standard adult equivalence factors defined in terms of sex and age [Baldwin 1987, Joseph 1990]. Children 0-14 years (0.5); adult women 14-59 years (0.8); adult men 14-59 years (1.0); elders 59 years and above (0.8).

Table B.2. Family size stratification.

Strata family size	Number of families	Percentage of total (%)
2-6	12	20.0
7-11	16	26.7
12-16	13	21.7
17-21	8	13.3
22+	11	18.3

Table B.3. Village population by month.

	Village population
Jan	750
Feb	821
Mar	821
Apr	821
May	821
Jun	749
Jul	736
Aug	736
Sep	736
Oct	750
Nov	750
Dec	750
Average	770

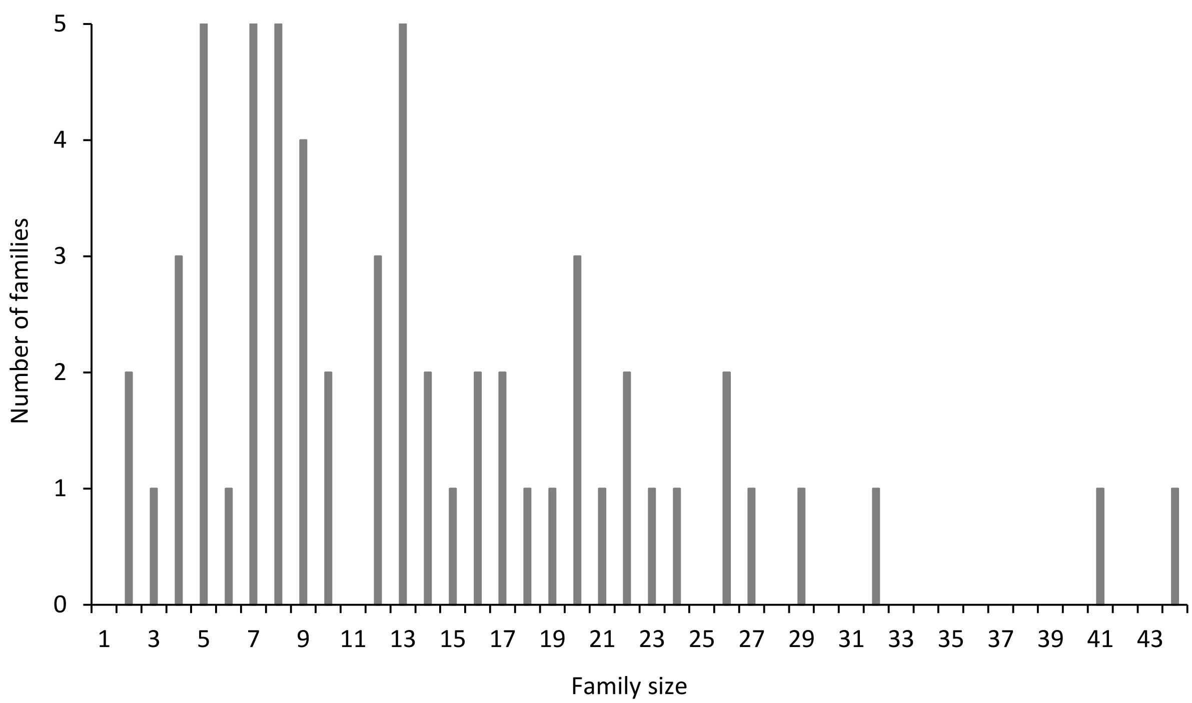


Figure B.1. Frequency distribution of family size.

APPENDIX C

PARTICIPANT OBSERVATION

Date | | Family | | Family ID | |

Energy application	Fuel type(s) used	Rate of the activity	Technology used	Person(s) in charge (M/F, Age)	Location(s) of use	Person(s) benefiting	Comments

Domestic fuel collection, storage, and use recorded on other sheets

Domestic energy collection and storage
Domestic lead-acid battery use
Lead-acid battery charge log
Wood collection survey
Solar panel survey (public service and domestic)
Energy sales shop questionnaire
Observational cooking test
Session cooking test
Daily cooking test

Date		Family		Family ID	

Energy	Who collects (M/F, Age)	Collected where?	Transport method	Amount	How long will energy last?	Time spent	Frequency	Rate
Wood								
Charcoal								
Kerosene								
Petrol								
Batteries								
Other								

Who has the primary roll of collecting wood? (summer/winter): ____________.

How many bundles of wood is needed for one day for all families? Women bundle (summer/winter): ________ Child bundle (sum/winter): ________.

How many days/weeks will wood last from one donkey cart? (summer/winter): _________.

Wood stock No.	Side A (wxh)	Side B (wxh)	Length	Volume (m^3)	Weight (kg)	Bulk Density (kg/m^3)

Comments

Participant observation of Family ID: F03

Date: May-14, 2009

Family size: 22 (15 children, 2 adult women, 2 adult men, 3 elderly)

Occupations: farmers, housewives, students

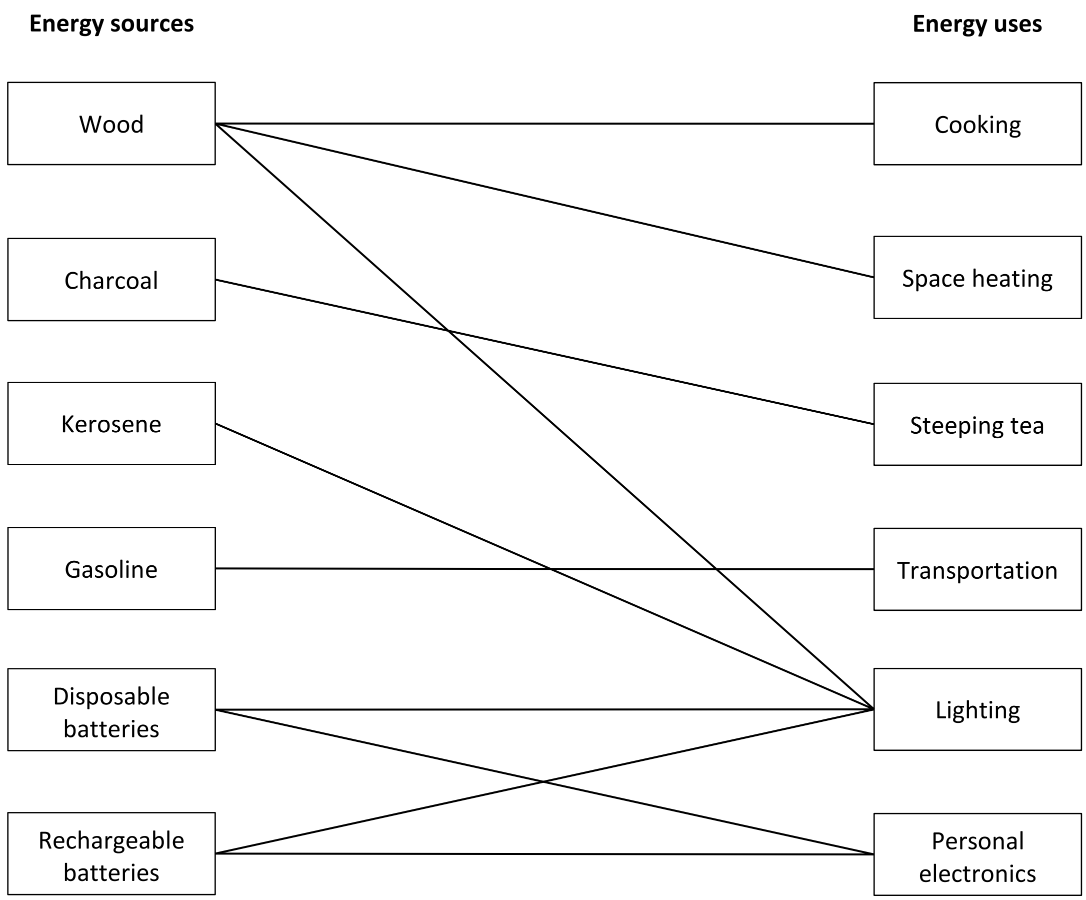


Figure C.1. Energy sources mapped to energy uses of selected household.

Table C.1. Wood store size.

	Wood store	
	Primary	Auxiliary
Mass (kg)	638.1	560.7
Size (m^3)	4.8	4.6
Bulk density (kg/m^3)	132.9	121.9

Table C.2. Daily activities for one adult woman of selected household.

Time of day	Activity
5:30 AM	Wake up
5:30 AM – 8:00 AM	Prepare and eat breakfast Sweep kitchen and household grounds Gather water Wash dishes Tend to children
8:00 AM – 9:00 AM	Garden
9:00 AM – 11:00 AM	Gather wood
11:00 AM – 2:00 PM	Prepare and eat lunch Gather water Wash dishes Tend to children
2:00 PM – 3:00 PM	Miscellaneous duties Tend to children
3:00 PM – 3:30 PM	Make tea for men
3:30 PM – 4:30 PM	Prepare grain for dinner and next day
4:30 PM – 5:30 PM	Take grain to grinder for processing
5:30 PM – 8:00 PM	Prepare and eat dinner Wash dishes Tend to children
8:00 PM – 9:00 PM	Make tea for men Tend to children
9:00 PM	Go to bed

Table C.3. Time-series data for cooking lunch.

Cooking test ID: Participant Observation 1 Time of day: lunch	Cookstove: three-stone fire No. fires: one
Meal: gnegnikini (grains) & gneguna (sauce) Location: indoor kitchen Cooking time (min): 80	Pot 1: sauce (leaves) Pot 2: grains (corn)

Time (hh:mm)	Activity
10:05	start fire with straw and lighter
10:08	add pot 1 to fire with water
	add lid to pot 1
	fan fire
10:10-10:15	cook outside of kitchen cutting leaves for sauce
10:15	check pot 1
	tend fire
10:25	remove lid on pot 1
	add leaves to pot 1
	tend fire
10:28	add spices to pot 1
10:28-10:34	constantly stir pot 1
10:39	tend fire
10:48	stir pot 1
10:52	remove pot 1 from fire
	add pot 2 to fire with water
10:52-11:03	cook left compound to get water
11:03	check pot 2
	tend fire
	fan fire
11:10	check pot 2
	add grains to pot 2
	stir pot 2
11:20	tend fire
11:25	remove pot 2 from fire
	end

Figure C.2. Activity diagram for cooking lunch showing parallel tasks.

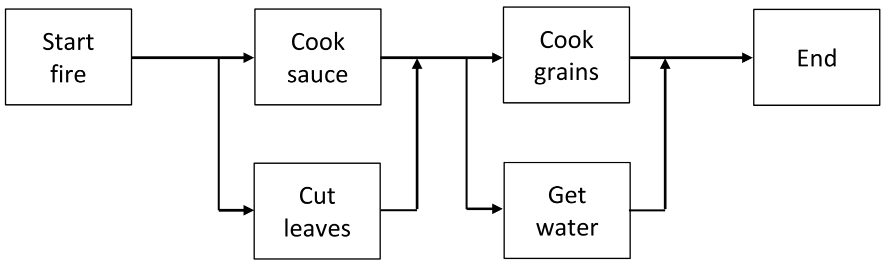
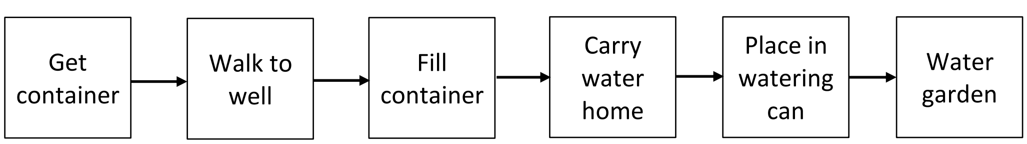


Figure C.3. Additional findings from observing cooking.

- Cookstove applications include meals and non-meal cooking needs.
- There are six meal types, two for breakfast and four that are often used interchangeably for lunch and dinner. Corn, millet, and rice are common grain types.
- Non-meal cookstove applications include heating water, processing shea, making medicine, roasting peanuts, and steeping tea.
- Multiple cooks share cooking duties for the extended family so that only one woman needs to cook for the extended family.
- Multiple cookstoves are owned and used for different types of meals and meal sizes. The three-stone fire is the most commonly used cookstove.
- Meals are preferred to be prepared inside a kitchen whereas hot water prepared outside the kitchen.
- Methods to start a fire include (a) a butane lighter with straw, (b) a butane lighter with plastic or trash, or (c) burning charcoal from another cooking fire.
- Pots of the same size can vary in thickness and mass by up to 50%.

Figure C.4. Activity diagram for gathering water and watering gardens.



APPENDIX D

DOMESTIC LEAD-ACID BATTERY USE QUESTIONNAIRE

Today's date		Family		Battery/Date			Family ID
		Transport method to/from home		Other location used(s), transport method			

Use	First use start date	All user(s)	Location (around home, out of home, etc.)	Days used per week	Average time per use	Ranked importance	Change during the year? Why?
Lighting social							
Lighting study							
Lighting snakes							
Lighting business							
Lighting other							
Radio							
Cell phone							
Other							

Table D.1. Domestic power applications of lead-acid batteries rented by families.

Application	No. responses[a]
Lighting social	26
Lighting study	8
Lighting snakes[b]	0
Lighting business[c]	2
Radio	10
Cell phone	9
Television	1

[a]Out of a total number of 28 families renting a lead-acid battery.
[b]The majority of families stated that lighting would help them see snakes, although no sightings of a snake were reported.
[c]Household business for making baskets.

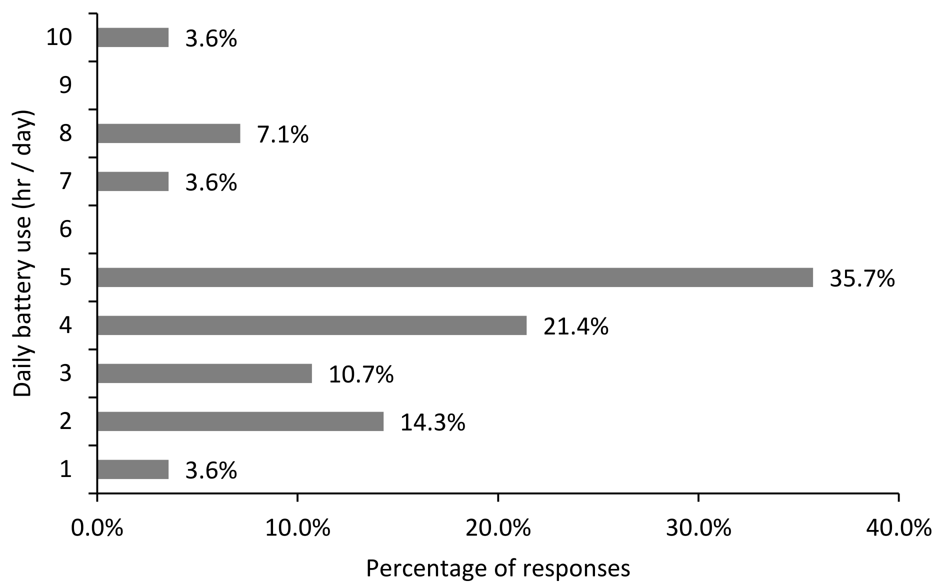


Figure D.1. Distribution of lead-acid battery use in hours per day for domestic applications.

APPENDIX E

DOMESTIC LEAD-ACID BATTERY CHARGE LOG

Battery No.	Drop-off date	Voltage before charge	Start time	End time	Voltage after charge	Pick up date	Paid	Client name

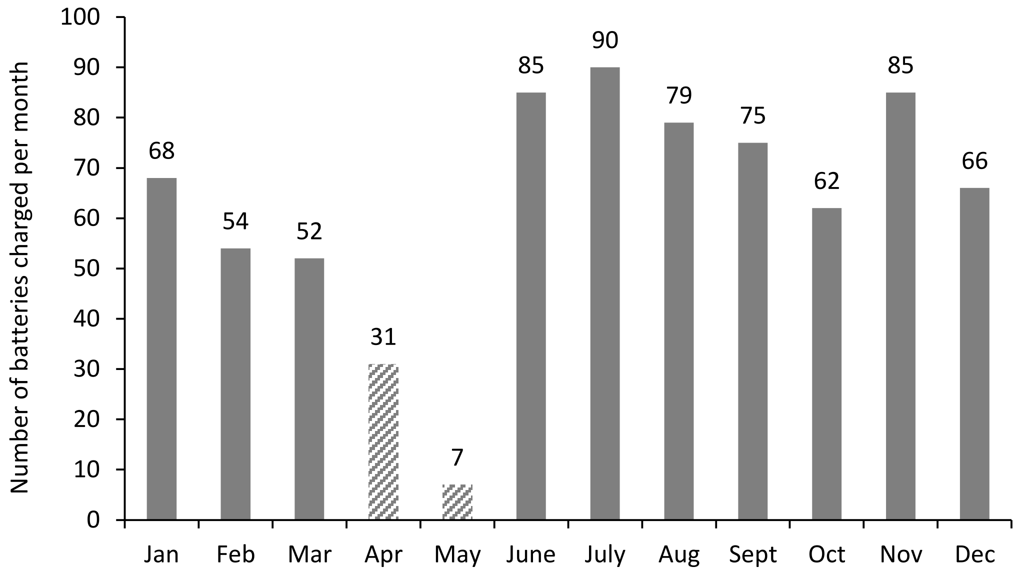


Figure E.1. Number of lead-acid battery charges per month at the battery charging business.[a]

[a]Charging records available for 10.5 months of the year with data missing from April and May. Total of 754 batteries charged in 10.5 months is scaled to a 12-month year at 862 batteries charged.

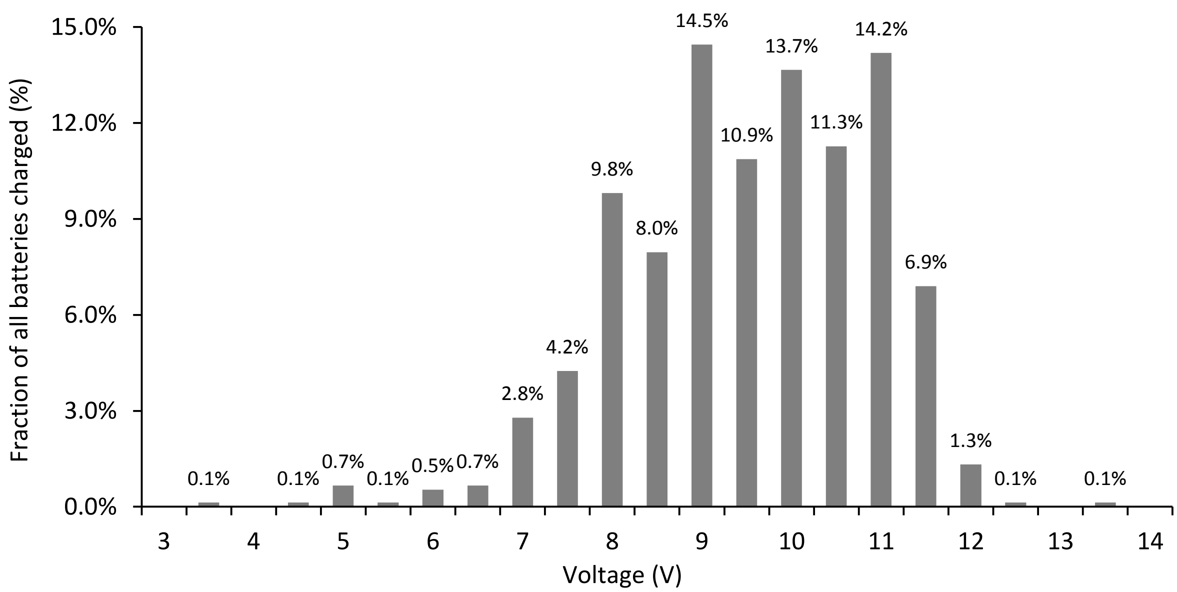


Figure E.2. Distribution of voltage for lead-acid batteries arriving at charging business.[a,b]

[a]Voltage before charge, mean = 9.79 V; σ = 1.37 V; max = 13.58 V, min = 3.79 V.
[b]Voltage after charge was 8V to 10V for 1% of batteries, 10V to 12V for 5% of batteries, and 12V to 13V for 94% of batteries leaving the battery charging station. One battery was less than 8V after charge and one battery was greater than 13V after charge. Mean = 12.34 V; σ = 0.50 V; max = 13.66 V, min = 6.52 V.

APPENDIX F

DOMESTIC WOOD COLLECTION SURVEY

Group No.	Date	Time of day	Respondent	M/F	Age	Location Measured	Wood type	Quantity (kg)	Location collected	Distance round-trip (km)	Total time to collect (min)	Collected how often? (days)

Table F.1. Wood collection mass of one head-load.

(a) Wood collection by adults.

Date	Time of day	Family ID	Gender (M/F)	Quantity (kg)
14-May-10	8:30	F01	F	21.0
28-May-10	17:00	F02	F	13.5
11-Aug-10	17:00	F01	F	14.5
11-Aug-10	18:00	F10	F	7.5
12-Aug-10	17:00	F10	F	19.0
12-Aug-10	17:30	F07	F	14.0
13-Aug-10	17:30	F01	F	22.0
13-Aug-10	18:00	F10	F	14.0
17-Aug-10	18:00	F01	F	17.0
17-Aug-10	18:00	F38	F	18.0
17-Aug-10	18:00	F09	F	21.0
20-Aug-10	17:30	F01	F	13.5
20-Aug-10	17:30	F02	F	21.0
20-Aug-10	17:30	F03	F	14.0
20-Aug-10	17:30	F38	F	24.0
20-Aug-10	17:30	F09	F	16.5
10-Dec-10	17:00	F03	F	17.5
10-Dec-10	17:00	F10	F	21.5
10-Dec-10	17:00	F12	F	15.0
11-Dec-10	17:15	F10	F	19.0

Table F.1 (continued). Wood collection mass of one head-load.

(b) Wood collection by children.

Date	Time of day	Family ID	Gender (M/F)	Quantity (kg)
14-May-10	8:30	F01	M	10.0
14-May-10	9:30	F03	M	3.0
28-May-10	17:00	F03	F	6.0
28-May-10	17:00	F03	F	10.0
28-May-10	17:00	F03	F	6.0
28-May-10	17:00	F04	F	8.0
28-May-10	17:00	F04	F	8.5
28-May-10	17:00	F04	F	11.0
28-May-10	17:00	F04	F	8.0
16-Aug-10	15:10	F03	M	10.0
17-Aug-10	18:00	F03	F	9.5

Notes:

- Wood is collected from family farmland; there is no communal area for wood collection.
- Family farmland is dispersed throughout the countryside; it is not centrally located.

Table F.2. Wood collection distance and time to collect.

Date	Time of day	Family ID	Gender M/F	Adult? (Y/N)	Quantity (kg)	Distance round-trip (km)	Total time to collect (min)
14-May-10	8:30	F01	F	Y	21.0	2.8	70
14-May-10	8:30	F01	M	N	10.0	2.8	-
13-Aug-10	17:30	F01	F	Y	22.0	8.4	170
10-Dec-10	17:00	F03	F	Y	17.5	3.8	100
10-Dec-10	17:00	F10	F	Y	21.5	6.2	120
10-Dec-10	17:00	F12	F	Y	15.0	6.8	-
11-Dec-10	17:15	F10	F	Y	19.0	6.2	-

Notes:

- Observations also shown in Table F1.

APPENDIX G

ARTISAN ENERGY USE SURVEY

Artisan type		Respondent		Artisan ID	

Fuel type	Fuel store No.	Dimensions w x h x l (m)	Mass (kg)	Bulk Density (kg / m3)

Equipment

Date	Activity	Fuel type	Fuel start (kg)	Fuel end (kg)	Rate of activity?	Seasonality

Comments:

Table G.1. Energy use data for cooking snacks.

Test ID	Wood name	Mass, as-received (kg)	Moisture content, as-received (wt%)	Energy use (MJ)[a]	Season
DCT_MS_01	gendu	1.645	7.65	26.007	cold and dry
DCT_MS_02	gendu	2.340	7.65	36.995	cold and dry
DCT_MS_03	gendu	1.985	7.65	31.383	cold and dry

[a]Mean = 31.5 MJ; σ = 5.5 MJ.

Table G.2. Energy use data for baking bread.

(a) Energy use for one batch of bread.[a]

Test ID	Wood name	Mass, as-received (kg)	Moisture content, as-received (wt%)	Energy use (MJ)[b]	Season
SCT_BB_01	krekrete	27.500	10.94	414.586	hot and dry
SCT_BB_02	krekrete	33.000	10.94	497.503	hot and dry
SCT_BB_03	krekrete	22.000	14.24	317.384	temperate and rainy
SCT_BB_04	krekrete	31.500	14.24	454.437	temperate and rainy
SCT_BB_05	krekrete	37.000	14.24	533.783	temperate and rainy
SCT_BB_06	krekrete	34.000	7.65	534.583	cold and dry

[a]One batch of bread uses 10 kg total wet ingredients: flour (7.700 kg), yeast (0.060 kg), sugar (0.200 kg), baking soda (0.040 kg), water (2.000 kg). One batch produces 55 loaves of bread.
[b]Mean = 458.7 MJ; σ = 83.5 MJ.

(b) Seasonal bread production rate.

Season	Month	Batches per week
hot and dry	February to May	1.0
temperate and rainy	June to October	1.5
cold and dry	November	1.0
cold and dry	December to January	0.5

Table G.3. Energy use data for carpentering.

Test ID	Wood name	Mass, as-received (kg)	Moisture content, as-received (wt%)	Energy use (MJ)[a]	Season
DCT_C_01	gendu	6.875	10.30	105.119	hot and dry
DCT_C_02	gendu	10.020	10.30	155.958	hot and dry
DCT_C_03	gendu	7.345	10.30	112.305	hot and dry

[a]Mean = 124.5 MJ; σ = 27.5 MJ.

Table G.4. Energy use data for blacksmithing.

(a) Repeated measurements of the mass of one charge[a] of charcoal.[b]

Measurement	1	2	3	4	5
Mass (kg)	6.595	6.385	7.095	6.435	6.550

[a]One charge corresponds to a local measurement unit, a hand-made bucket.
[b]Using moisture content of 1.50% by weight on an as-received basis, mean = 188.9 MJ; σ = 8.1 MJ.

(b) Seasonal blacksmithing energy use.

Season	Month	Charges per week
hot and dry	April to May	21
temperate and rainy	June to September	3
temperate and rainy / cold and dry	October to December 15	0
cold and dry / hot and dry	December 16 to March	2

APPENDIX H

GRAIN GRINDER ENERGY USE SURVEY

Date	
Corn Small millet Millet Peanut Shea Rice	
Total cans Total mass (kg)	
Diesel (L) Fuel consumption (mL / can) Fuel consumption (mL / kg)	
Revenue (CFA) Cost, fuel only (CFA) Profit (CFA) Profit per can (CFA / can)	

Per can conversations

Grain type	**Mass (kg)**	**Cost (CFA)**
Corn		
Small millet		
Millet		
Peanut		
Shea		
Rice		
Diesel cost (CFA / L)		

Diesel consumption by season (L / week)

	Wet	Cold
Grain		
Shea		
Total		

Comments

Table H.1. Energy use and economic data for diesel grain grinder.

Test ID	SCT_GG_01	SCT_GG_02	SCT_GG_03	SCT_GG_04	SCT_GG_05	SCT_GG_06	SCT_GG_07
Season	temperate and rainy	temperate and rainy	temperate and rainy	temperate and rainy	temperate and rainy	cold and dry	cold and dry
Corn	54	44	44		41	97	68
Small millet	2	1	2		1		
Millet	41	33	20		9	17	9
Peanut						10	
Shea				83			
Total cans	97	78	66	83	51	124	77
Total mass (kg)	176	141	119	116	91	219	137
Diesel (L)	0.82	1.28	0.8	1.55	0.75	1.32	0.85
Fuel consumption (mL / can)	8.45	16.41	12.12	18.67	14.71	10.65	11.04
Fuel consumption (mL / kg)	4.67	9.06	6.75	13.34	8.26	6.03	6.22
Revenue (CFA)	2695	2170	1870	4150	1480	3735	2265
Cost, fuel only (CFA)	574	896	560	1085	525	924	595
Profit (CFA)	2121	1274	1310	3065	955	2811	1670
Profit per can (CFA / can)	22	16	20	37	19	23	22

Table H.2. Mass of one can grain and cost to consumer to process.

Grain type	Mass (kg)	Cost (CFA)
Corn	1.76	30
Small millet	1.76	25
Millet	1.88	25
Peanut	1.61	40
Shea	1.40	50

Notes:

- Operator states he grinds for about two hours per day, and uses about one liter of diesel per day.
- Operator states he uses 5-10 L of diesel per week.
- Grinds shea on Fridays during the shea season, July through October.
- Diesel costs: 700 CFA (Aug 2010), 600 CFA (Dec 2010), purchased from market outside of the village and not from local energy shops.
- Exchange rate is $1USD = 500 CFA.

APPENDIX I

SOLAR PANEL CAPACITY SURVEY

Village	Location	Panel rating (W)	No. panels	Total rating (W)	Direction	Rise (in)	Run (in)	Angle from horizontal	Manufacturer	Model No.	Specs

Table I.1. Solar panel survey data.

Location	Rated solar power			Azimuth (degrees W of S)	Slope (degrees)	Manufacturer	Model No.
	Panel (W)	Quantity	Array (W)				
School East	75	1	75	-10	40	Solar Sales Photovoltaics	SP75W
School Center	75	1	75	0	43	Solar Sales Photovoltaics	SP75W
School Center[a]	57	1	57	5	23	Neste	NM57
School West	75	1	75	0	25	Solar Sales Photovoltaics	SP75W
Banana charging station	80	4	320	-70	2	Sharp	NE80E1EA
Banana charging station	110	2	220	-70	7	Kyocera	KC110-1
Water tower	75	13	975	0	15	Siemens	SP75W
Water tower	70	5	350	0	15	Siemens	SP70W
Clinic	70	8	560	10	15	Siemens	SP70W
Lanceni compound 1	55	2	110	10	7	Siemens	SM55
Lanceni compound 2	55	1	55	10	12	Siemens	SM55
Nurse's home	55	1	55	10	7	Photowatt Technologies	PMX500
School teacher's home	55	1	55	10	7	Photowatt Technologies	PMX500

[a]Library; room locked and not used. Panel added to total panel count in village but rated capacity not included in village energy use computation because energy from the panel is not used.

APPENDIX J

ENERGY SALES SHOP SURVEY

Fuel costs in Nana Kenieba

Fuel	Amount	Cost (CFA)	Cost (USD)	Date	Location(s) obtained	Comments
Kerosene						
Gas						
D battery						
AA battery						
AAA battery						
Diesel						
Candle						
Lighter						

Vendor purchasing rate from Siby

Fuel	Amount	Rate	Vendor	Date	Comments
Kerosene					
Gas					
D battery					
AA battery					
AAA battery					
Diesel					
Candle					
Lighter					
Kerosene					
Gas					
D battery					
AA battery					
AAA battery					
Diesel					
Candle					
Lighter					

Table J.1. Monthly sales volume to the village as estimated by energy shop owners.

Fuel	Weekly sales by month[a]												Annual sales[b]
	Jan[f]	Feb[f]	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
D battery (count)	480	480	240	240	240	240	240	240	240	240	240	240	14500
AA battery (count)	144	144	72	72	72	72	72	72	72	72	72	72	4400
AAA battery (count)	60	60	30	30	30	30	30	30	30	30	30	30	1800
Kerosene (L)[c]	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	480
Gas (L)	125	125	100	100	100	60	60	60	60	60	60	60	4200
Diesel (L)[d]	0	0	0	0	0	0	0	0	0	0	0	0	0
Candles (count)[e]	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	80
Butane lighter (count)	2	2	2	2	2	2	2	2	2	2	2	2	100

[a]Quantities shown on weekly basis due to differences in number of days per month.
[b]Numbers rounded.
[c]Kerosene sales at ten liters per month., shown above as 9.2 candles per week.
[d]Diesel is sold in small quantities to trucks passing through the village. Diesel sold by the shop owners is not used by the village and not included in overall village energy use quantities.
[e]Candle sales at seven candles per month, shown above as 1.6 candles per week.
[f]Gasoline and battery purchases are higher in January and February following harvest when more disposable income is available relative to other months.

Table J.2. Observed weekly energy sales rates by season for Shop A.

Fuel	Quantity ordered for one week			
	19-May-10	14-Aug-10	11-Dec-10	18-Dec-10
D battery (count)	120	120	120	120
AA battery (count)	24	24	20	24
AAA battery (count)	0	60	60	0
Kerosene (L)	20	0	0	0
Gas (L)	50	25	25	50
Diesel (L)	0	0	0	0
Candles (count)	0	0	0	0
Butane lighter (count)	0	0	0	0

Table J.3. Observed weekly energy sales rates by season for Shop B.

Fuel	Quantity ordered for one week			
	19-May-10	14-Aug-10	11-Dec-10	18-Dec-10
D battery (count)	120	240	120	120
AA battery (count)	48	48	72	48
AAA battery (count)	60	60	0	60
Kerosene (L)	20	24	20	0
Gas (L)	50	50	50	25
Diesel (L)	0	0	0	0
Candles (count)	0	0	0	0
Butane lighter (count)	0	10	20	0

Table J.4. Price of energy at small sales shops in the village.

Fuel	Amount	Price	
		CFA[a]	USD ($)[b]
Kerosene	70 mL	50	0.1
Gas	1 liter	750	1.5
D battery	1 battery	100	0.2
AA battery	1 battery	75	0.15
AAA battery	1 battery	75	0.15
Diesel	1 liter	750	1.5
Candle	8" tall 1/2" dia	50	0.1
Butane lighter	1 lighter	225	0.45

[a]Data obtained in May 2010.
[b]Exchange rate is $1USD = 500 CFA

APPENDIX K

DOMESTIC COOKSTOVE OWNERSHIP AND USE SURVEY

Date		Husband		Head male		Family ID	

Cook ID	
	1.
	2.
	3.
	4.

No. eating	
	Child
	Adult
	Grandparent
	Total

Cook ID	In/Outdoor	Stove type	Quantity	Use how often?

Meal	Time of day? (BLD)	How often eat? (e.g., daily)	Stove(s) used?	Comment(s)
Monie				
Serie				
Gnegnekini & gneguna				
Toh & sauce				
Rice & sauce				
Cous cous				
Hot water				
Peanuts				
Tea				
Medicine				

How do you choose between indoor or outdoor kitchen? Type of meal? Type of stove? Weather related?

Do you share cooking duties with others? If so, who? Does this change by season?

Do you cook only for your children, or for the entire family of your husband? For any of his brother's and their family?

Additional comments

Table K.1. Number of cookstoves in the village.

(a) For all cooks.

Cookstove type	Number of cookstoves (% of total in village)		
	Total	Inside	Outside
Three-stone fire	296 (81.1)	152 (41.6)	144 (39.5)
Gakourouwana	19 (5.2)	15 (4.1)	4 (1.1)
Low thermal capacity	36 (9.9)	34 (9.3)	2 (0.6)
Hand-crafted metal	8 (2.2)	8 (2.2)	0 (0.0)
Manufactured metal	6 (1.6)	6 (1.6)	0 (0.0)
Totals	365 (100.0)	215 (58.9)	150 1.1)

(b) For all cooks who prepare meals and may heat water.

Cookstove type	Number of cookstoves (% of total in village)		
	Total	Inside	Outside
Three-stone fire	277 (80.3)	145 (42)	132 (38.3)
Gakourouwana	19 (5.5)	15 (4.4)	4 (1.2)
Low thermal capacity	35 (10.1)	33 (9.6)	2 (0.6)
Hand-crafted metal	8 (2.3)	8 (2.3)	0 (0.0)
Manufactured metal	6 (1.7)	6 (1.7)	0 (0.0)
Totals	345 (100.0)	207 (60.0)	138 0.0)

(c) For all cooks who only heat water and do no prepare meals.

Cookstove type	Number of cookstoves (% of total in village)		
	Total (%)	Inside (%)	Outside (%)
Three-stone fire	19 (95.0)	7 (35.0)	12 (60.0)
Gakourouwana	0 (0.0)	0 (0.0)	0 (0.0)
Low thermal capacity	1 (5.0)	1 (5.0)	0 (0.0)
Hand-crafted metal	0 (0.0)	0 (0.0)	0 (0.0)
Manufactured metal	0 (0.0)	0 (0.0)	0 (0.0)
Totals	20 (100.0)	8 (40.0)	12 (60.0)

Table K.2. Cookstove ownership groups.

Number of cookstoves (% of total cooks)	Ownership group ID	Number of cooks	Cookstove ownership[a] TSF	GK	LTC	HCM	MM
1 cookstove (52.0%)	1A	63	X				
	1B	1		X			
2 cookstoves (35.8%)	2A	29	X		X		
	2B	6	X			X	
	2C	5	X	X			
	2D	3	X				X
	2E	1		X	X		
3 cookstoves (8.1%)	3A	5	X	X	X		
	3B	3	X	X			X
	3C	1	X		X	X	
	3D	1	X		X		X
4 cookstoves (2.4%)	4A	3	X	X	X	X	
5 cookstoves (1.6%)	5A	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%)

[a]Three-stone fire (TSF), gakourouwana (GK), low thermal capacity (LTC), hand-crafted metal (HCM), manufactured metal (MM).

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.

Table K.3. Meal names in Bamakan and English.

Bamakan	English
Monie	Breakfast porridge (thin)
Serie	Breakfast porridge (thick)
Gnegnekini & gneguna	Meal porridge (thin) with sauce
Toh & na	Meal porridge (thick) with sauce
Riz	Rice
Couscous	Couscous

Table K.4. Cookstove use and meal preparation fractions for all combinations of cookstove ownership in the village.

Notes: Cookstove use and meal preparation fractions are calculated through knowledge of the frequency of occurrence that each meal is prepared and the fraction each cookstove is used to prepare each meal for each cook in the village. Seasonal changes in the number of cooks in the village, meals prepared, and cookstove use are factored into the aggregate numbers. Below data shown for the 115 women cooking meals; data for the eight women who heat water and do not cook meals has been removed (seven cooks from ownership group A1 and one cook from ownership group 2A).

(a) Cookstove use for entire village.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1683	0.7351	0.2232	0.0083	0.0298	0.0037
Monie	0.1708	0.8207	0.1631	0.0045	0.0103	0.0015
Gnegnekini & gneguna[c]	0.3393	0.7778	0.2145	0.0034	0.0043	0.0000
Toh & na[c]	0.2123	0.7916	0.1991	0.0008	0.0085	0.0000
Riz	0.0262	0.6828	0.0838	0.0000	0.2334	0.0000
Couscous	0.0368	0.6819	0.3174	0.0007	0.0000	0.0000
Grain[d]	0.0464	0.8130	0.1825	0.0000	0.0045	0.0000
Sauce[d]		0.0000	0.0000	0.3352	0.3848	0.2799
No. of cooks that own cookstove		113	20	41	12	9

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(b) Cookstove use conditioned by ownership of a three-stone fire.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1684	0.7487	0.2093	0.0079	0.0303	0.0038
Monie	0.1708	0.8357	0.1483	0.0040	0.0105	0.0015
Gnegnekini & gneguna[c]	0.3394	0.7916	0.2011	0.0029	0.0044	0.0000
Toh & na[c]	0.2109	0.8112	0.1793	0.0008	0.0087	0.0000
Riz	0.0267	0.6828	0.0838	0.0000	0.2334	0.0000
Couscous	0.0366	0.6986	0.3014	0.0000	0.0000	0.0000
Grain[d]	0.0472	0.8130	0.1825	0.0000	0.0045	0.0000
Sauce[d]		0.0000	0.0000	0.3352	0.3848	0.2799
No. of cooks that own cookstove		113	18	40	12	9

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(c) Cookstove use conditioned by ownership of a gakourouwana cookstove.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1938	0.0307	0.9094	0.0022	0.0425	0.0152
Monie	0.1464	0.0406	0.8922	0.0029	0.0562	0.0080
Gnegnekini & gneguna[c]	0.3518	0.0377	0.9409	0.0023	0.0191	0.0000
Toh & na[c]	0.2001	0.0486	0.9466	0.0000	0.0048	0.0000
Riz	0.0123	0.1667	0.8333	0.0000	0.0000	0.0000
Couscous	0.0549	0.0000	0.9978	0.0022	0.0000	0.0000
Grain[d]	0.0407	0.0000	0.9759	0.0000	0.0241	0.0000
Sauce[d]		0.0000	0.0000	0.2916	0.0000	0.7084
No. of cooks that own cookstove		18	20	11	5	5

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(d) Cookstove use conditioned by ownership of a low thermal capacity cookstove.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1685	0.6395	0.3022	0.0215	0.0271	0.0097
Monie	0.1649	0.6830	0.2733	0.0121	0.0277	0.0040
Gnegnekini & gneguna[c]	0.3354	0.6496	0.3306	0.0086	0.0112	0.0000
Toh & na[c]	0.2153	0.7133	0.2823	0.0019	0.0025	0.0000
Riz	0.0195	0.7078	0.2922	0.0000	0.0000	0.0000
Couscous	0.0546	0.5889	0.4099	0.0012	0.0000	0.0000
Grain[d]	0.0419	0.8429	0.1441	0.0000	0.0130	0.0000
Sauce[d]		0.0000	0.0000	0.9659	0.0000	0.0341
No. of cooks that own cookstove		40	11	41	6	3

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(e) Cookstove use conditioned by ownership of a hand-crafted metal cookstove.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1798	0.2693	0.4496	0.0000	0.2498	0.0312
Monie	0.1496	0.3961	0.4839	0.0000	0.1050	0.0150
Gnegnekini & gneguna[c]	0.2061	0.0586	0.8828	0.0000	0.0586	0.0000
Toh & na[c]	0.1423	0.1139	0.7594	0.0000	0.1267	0.0000
Riz	0.0904	0.2205	0.1739	0.0000	0.6056	0.0000
Couscous	0.0550	0.1429	0.8571	0.0000	0.0000	0.0000
Grain[d]	0.1768	0.9037	0.0857	0.0000	0.0106	0.0000
Sauce[d]		0.0000	0.0000	0.0963	0.9037	0.0000
No. of cooks that own cookstove		12	5	6	12	2

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(f) Cookstove use conditioned by ownership of a manufactured metal cookstove.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.2323	0.3490	0.5841	0.0194	0.0000	0.0475
Monie	0.1010	0.8025	0.1092	0.0446	0.0000	0.0437
Gnegnekini & gneguna[c]	0.1949	0.2336	0.6642	0.0000	0.1022	0.0000
Toh & na[c]	0.1146	0.3077	0.6703	0.0000	0.0220	0.0000
Riz	0.0309	1.0000	0.0000	0.0000	0.0000	0.0000
Couscous	0.0849	1.0000	0.0000	0.0000	0.0000	0.0000
Grain[d]	0.2413	0.4987	0.4861	0.0000	0.0152	0.0000
Sauce[d]		0.0000	0.0000	0.0533	0.0000	0.9467
No. of cooks that own cookstove		9	5	3	2	9

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(g) Cookstove use conditioned by ownership of at least one improved cookstove

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1767	0.5937	0.3191	0.0173	0.0622	0.0078
Monie	0.1557	0.7171	0.2439	0.0108	0.0247	0.0035
Gnegnekini & gneguna[c]	0.2861	0.6218	0.3592	0.0083	0.0107	0.0000
Toh & na[c]	0.1953	0.6556	0.3233	0.0017	0.0193	0.0000
Riz	0.0347	0.4758	0.1385	0.0000	0.3857	0.0000
Couscous	0.0499	0.6206	0.3783	0.0011	0.0000	0.0000
Grain[d]	0.1016	0.8130	0.1825	0.0000	0.0045	0.0000
Sauce[d]		0.0000	0.0000	0.3352	0.3848	0.2799
No. of cooks that own cookstove		52	14	41	12	9

Note: Improved cookstoves include the low thermal capacity cookstove, the hand-crafted metal cookstove, and the manufactured metal cookstove.

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(h) Cookstove use conditioned by ownership of no improved cookstove.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1614	0.8649	0.1351	0.0000	0.0000	0.0000
Monie	0.1834	0.8943	0.1057	0.0000	0.0000	0.0000
Gnegnekini & gneguna[c]	0.3858	0.8845	0.1155	0.0000	0.0000	0.0000
Toh & na[c]	0.2247	0.8979	0.1021	0.0000	0.0000	0.0000
Riz	0.0190	1.0000	0.0000	0.0000	0.0000	0.0000
Couscous	0.0258	0.7813	0.2188	0.0000	0.0000	0.0000
Grain[d]	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sauce[d]		0.0000	0.0000	0.0000	0.0000	0.0000
No. of cooks that own cookstove		61	6	0	0	0

Note: Improved cookstoves include the low thermal capacity cookstove, the hand-crafted metal cookstove, and the manufactured metal cookstove.

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(i) Cookstove use for cookstove ownership group 1A.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1577	1.0000	0.0000	0.0000	0.0000	0.0000
Monie	0.1856	1.0000	0.0000	0.0000	0.0000	0.0000
Gnegnekini & gneguna[c]	0.3850	1.0000	0.0000	0.0000	0.0000	0.0000
Toh & na[c]	0.2271	1.0000	0.0000	0.0000	0.0000	0.0000
Riz	0.0216	1.0000	0.0000	0.0000	0.0000	0.0000
Couscous	0.0229	1.0000	0.0000	0.0000	0.0000	0.0000
Grain[d]	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sauce[d]		0.0000	0.0000	0.0000	0.0000	0.0000
No. of cooks that own cookstove		56	0	0	0	0

Note: Cookstove ownership group description given in Table K2.

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(j) Cookstove use for cookstove ownership group 1B.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1667	0.0000	1.0000	0.0000	0.0000	0.0000
Monie	0.1667	0.0000	1.0000	0.0000	0.0000	0.0000
Gnegnekini & gneguna[c]	0.3333	0.0000	1.0000	0.0000	0.0000	0.0000
Toh & na[c]	0.2857	0.0000	1.0000	0.0000	0.0000	0.0000
Riz	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Couscous	0.0476	0.0000	1.0000	0.0000	0.0000	0.0000
Grain[d]	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sauce[d]		0.0000	0.0000	0.0000	0.0000	0.0000
No. of cooks that own cookstove		0	1	0	0	0

Note: Cookstove ownership group description given in Table K2.

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(k) Cookstove use for cookstove ownership group 2A.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1640	0.9726	0.0000	0.0274	0.0000	0.0000
Monie	0.1693	0.9894	0.0000	0.0106	0.0000	0.0000
Gnegnekini & gneguna[c]	0.3327	0.9880	0.0000	0.0120	0.0000	0.0000
Toh & na[c]	0.2284	0.9971	0.0000	0.0029	0.0000	0.0000
Riz	0.0134	1.0000	0.0000	0.0000	0.0000	0.0000
Couscous	0.0362	1.0000	0.0000	0.0000	0.0000	0.0000
Grain[d]	0.0560	1.0000	0.0000	0.0000	0.0000	0.0000
Sauce[d]		0.0000	0.0000	1.0000	0.0000	0.0000
No. of cooks that own cookstove		28	0	28	0	0

Note: Cookstove ownership group description given in Table K2.

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(l) Cookstove use for cookstove ownership group 2B.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1856	0.5873	0.0000	0.0000	0.4127	0.0000
Monie	0.1375	1.0000	0.0000	0.0000	0.0000	0.0000
Gnegnekini & gneguna[c]	0.0178	0.0000	0.0000	0.0000	0.0000	0.0000
Toh & na[c]	0.0234	0.0714	0.0000	0.0000	0.9286	0.0000
Riz	0.1959	0.2669	0.0000	0.0000	0.7331	0.0000
Couscous	0.0206	1.0000	0.0000	0.0000	0.0000	0.0000
Grain[d]	0.4192	1.0000	0.0000	0.0000	0.0000	0.0000
Sauce[d]		0.0000	0.0000	0.0000	1.0000	0.0000
No. of cooks that own cookstove		6	0	0	6	0

Note: Cookstove ownership group description given in Table K2.

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(m) Cookstove use for cookstove ownership group 2C.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1912	0.0463	0.9537	0.0000	0.0000	0.0000
Monie	0.1680	0.0527	0.9473	0.0000	0.0000	0.0000
Gnegnekini & gneguna[c]	0.4005	0.0664	0.9336	0.0000	0.0000	0.0000
Toh & na[c]	0.1938	0.1029	0.8971	0.0000	0.0000	0.0000
Riz	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Couscous	0.0465	0.0000	1.0000	0.0000	0.0000	0.0000
Grain[d]	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sauce[d]		0.0000	0.0000	0.0000	0.0000	0.0000
No. of cooks that own cookstove		5	5	0	0	0

Note: Cookstove ownership group description given in Table K2.

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(n) Cookstove use for cookstove ownership group 2D.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1667	1.0000	0.0000	0.0000	0.0000	0.0000
Monie	0.1667	1.0000	0.0000	0.0000	0.0000	0.0000
Gnegnekini & gneguna[c]	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Toh & na[c]	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Riz	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Couscous	0.0816	1.0000	0.0000	0.0000	0.0000	0.0000
Grain[d]	0.5850	1.0000	0.0000	0.0000	0.0000	0.0000
Sauce[d]		0.0000	0.0000	0.0000	0.0000	1.0000
No. of cooks that own cookstove		3	0	0	0	3

Note: Cookstove ownership group description given in Table K2.

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(o) Cookstove use for cookstove ownership group 2E.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1667	0.0000	0.9405	0.0595	0.0000	0.0000
Monie	0.1667	0.0000	0.9405	0.0595	0.0000	0.0000
Gnegnekini & gneguna[c]	0.3333	0.0000	0.9405	0.0595	0.0000	0.0000
Toh & na[c]	0.2857	0.0000	1.0000	0.0000	0.0000	0.0000
Riz	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Couscous	0.0476	0.0000	0.9405	0.0595	0.0000	0.0000
Grain[d]	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sauce[d]		0.0000	0.0000	0.0000	0.0000	0.0000
No. of cooks that own cookstove		0	1	1	0	0

Note: Cookstove ownership group description given in Table K2.

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(p) Cookstove use for cookstove ownership group 3A.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1786	0.0778	0.9222	0.0000	0.0000	0.0000
Monie	0.1548	0.0897	0.9103	0.0000	0.0000	0.0000
Gnegnekini & gneguna[c]	0.3711	0.0734	0.9266	0.0000	0.0000	0.0000
Toh & na[c]	0.2154	0.0904	0.9096	0.0000	0.0000	0.0000
Riz	0.0159	0.5000	0.5000	0.0000	0.0000	0.0000
Couscous	0.0529	0.0000	1.0000	0.0000	0.0000	0.0000
Grain[d]	0.0113	0.0000	1.0000	0.0000	0.0000	0.0000
Sauce[d]		0.0000	0.0000	1.0000	0.0000	0.0000
No. of cooks that own cookstove		5	5	5	0	0

Note: Cookstove ownership group description given in Table K2.

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(q) Cookstove use for cookstove ownership group 3B.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.3333	0.0000	1.0000	0.0000	0.0000	0.0000
Monie	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Gnegnekini & gneguna[c]	0.1667	0.0000	1.0000	0.0000	0.0000	0.0000
Toh & na[c]	0.1667	0.0000	1.0000	0.0000	0.0000	0.0000
Riz	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Couscous	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Grain[d]	0.3333	0.0000	1.0000	0.0000	0.0000	0.0000
Sauce[d]		0.0000	0.0000	0.0000	0.0000	1.0000
No. of cooks that own cookstove		3	3	0	0	3

Note: Cookstove ownership group description given in Table K2.

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(r) Cookstove use for cookstove ownership group 3C.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1667	1.0000	0.0000	0.0000	0.0000	0.0000
Monie	0.1667	1.0000	0.0000	0.0000	0.0000	0.0000
Gnegnekini & gneguna[c]	0.3333	1.0000	0.0000	0.0000	0.0000	0.0000
Toh & na[c]	0.3333	1.0000	0.0000	0.0000	0.0000	0.0000
Riz	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Couscous	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Grain[d]	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sauce[d]		0.0000	0.0000	0.0000	0.0000	0.0000
No. of cooks that own cookstove		1	0	1	1	0

Note: Cookstove ownership group description given in Table K2.

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(s) Cookstove use for cookstove ownership group 3D.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1667	0.9167	0.0000	0.0833	0.0000	0.0000
Monie	0.1667	0.9167	0.0000	0.0833	0.0000	0.0000
Gnegnekini & gneguna[c]	0.1746	1.0000	0.0000	0.0000	0.0000	0.0000
Toh & na[c]	0.1528	1.0000	0.0000	0.0000	0.0000	0.0000
Riz	0.0952	1.0000	0.0000	0.0000	0.0000	0.0000
Couscous	0.2143	1.0000	0.0000	0.0000	0.0000	0.0000
Grain[d]	0.0298	1.0000	0.0000	0.0000	0.0000	0.0000
Sauce[d]		0.0000	0.0000	0.0000	0.0000	1.0000
No. of cooks that own cookstove		1	0	1	0	1

Note: Cookstove ownership group description given in Table K2.

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(t) Cookstove use for cookstove ownership group 4A.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.1667	0.0000	0.8095	0.0000	0.1905	0.0000
Monie	0.1667	0.0000	0.8095	0.0000	0.1905	0.0000
Gnegnekini & gneguna[c]	0.3355	0.0000	1.0000	0.0000	0.0000	0.0000
Toh & na[c]	0.1830	0.0000	1.0000	0.0000	0.0000	0.0000
Riz	0.0317	0.0000	1.0000	0.0000	0.0000	0.0000
Couscous	0.0952	0.0000	1.0000	0.0000	0.0000	0.0000
Grain[d]	0.0212	0.0000	1.0000	0.0000	0.0000	0.0000
Sauce[d]		0.0000	0.0000	1.0000	0.0000	0.0000
No. of cooks that own cookstove		3	3	3	3	0

Note: Cookstove ownership group description given in Table K2.

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

(u) Cookstove use for cookstove ownership group 5A.

Meal	Fraction of all meals prepared[a]	Fraction of meals prepared on cookstove[b]				
		TSF	GK	LTC	HCM	MM
Serie	0.2381	0.0000	0.7143	0.0000	0.0000	0.2857
Monie	0.0952	0.0000	0.7143	0.0000	0.0000	0.2857
Gnegnekini & gneguna[c]	0.5139	0.0000	0.7143	0.0000	0.2857	0.0000
Toh & na[c]	0.0734	0.0000	0.7143	0.0000	0.2857	0.0000
Riz	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Couscous	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Grain[d]	0.0794	0.0000	0.7143	0.0000	0.2857	0.0000
Sauce[d]		0.0000	0.0000	1.0000	0.0000	0.0000
No. of cooks that own cookstove		2	2	2	2	2

Note: Cookstove ownership group description given in Table K2.

[a]Column may not sum to 100% due to rounding.
[b]Rows may not sum to 100% due to rounding.
[c]Meals that have a grain component and a sauce component.
[d]Indicates grain and sauce meals (note c) that are prepared on two different types of cookstoves.

APPENDIX L

OBSERVATIONAL COOKING TEST

Date		Head male		Family ID	
Time		Cook		No. eating	
Cooking application		Ignition method		Cooking Location	
Ambient temp (C)		Cookstove type(s)		Cooking order	sequence OR parallel

Fuel type and name	Start (kg)	End (kg)	Used (kg)	Pot No(s).
Igniter				
Char end				

Pot No.	Pot size and mass (kg)	Cooking description

Ingredient	Pot (kg)	Pot with ingred. (kg)	Ingred. (kg)	Pot No.?	Comments (e.g., coarse ground flour)

Total mass	Start (kg)	End (kg)	Diff (kg)
Pot 1			
Pot 2			

Time (hh:mm)	Activity	Time (hh:mm)	Activity

Additional comments

Table L.1. Observational Cooking Test data for cooking meals.

Test ID	Number of people	Stand. adult equiv.[a]	Family ID	Meal time of day	Meal type	Grain type	Sauce type
OCT_M_01	5	3.3	F02	dinner	couscous	rice	N/A
OCT_M_02	22	13.5	F01	breakfast	serie	corn	N/A
OCT_M_03	22	13.5	F01	lunch	gnegnekini & gneguna	corn	leaves
OCT_M_04	22	13.5	F01	dinner	toh & na	corn	leaves
OCT_M_05	22	13.5	F01	breakfast	monie	corn	N/A
OCT_M_06	22	13.5	F01	lunch	gnegnekini & gneguna	rice	peanut
OCT_M_07	20	12.8	F03	breakfast	serie	millet	N/A
OCT_M_08	20	12.8	F03	lunch	gnegnekini & gneguna	rice	leaves
OCT_M_09	20	12.8	F03	dinner	toh & na	corn	leaves
OCT_M_10	18	11.9	F04	breakfast	serie	rice	N/A
OCT_M_11	18	11.9	F04	lunch	gnegnekini & gneguna	rice	leaves
OCT_M_12	18	11.9	F04	dinner	toh & na	rice	leaves
OCT_M_13	20	13.0	F05	breakfast	monie	corn	N/A
OCT_M_14	10	6.7	F01	breakfast	serie	millet	N/A
OCT_M_15	10	6.7	F01	lunch	gnegnekini & gneguna	corn	leaves
OCT_M_16	10	6.7	F01	dinner	couscous	corn	N/A
OCT_M_17	12	7.4	F07	breakfast	serie	rice	N/A
OCT_M_18	12	7.4	F07	lunch	gnegnekini & gneguna	rice	peanut
OCT_M_19	20	12.8	F03	breakfast	serie	millet	N/A
OCT_M_20	20	12.8	F03	lunch	gnegnekini & gneguna	millet	peanut
OCT_M_21	20	12.8	F03	dinner	toh & na	millet	leaves
OCT_M_22	23	14.5	F10	dinner	gnegnekini & gneguna	corn	leaves
OCT_M_23	20	12.8	F03	lunch	gnegnekini & gneguna	millet	leaves
OCT_M_24	20	12.8	F03	dinner	gnegnekini & gneguna	millet	peanut
OCT_M_25	5	3.3	F02	breakfast	monie	corn	N/A
OCT_M_26	5	3.3	F02	lunch	gnegnekini & gneguna	rice	leaves
OCT_M_27	5	3.3	F02	dinner	couscous	rice	N/A
OCT_M_28	9	6.7	F09	breakfast	serie	millet	N/A
OCT_M_29	9	6.7	F09	lunch	gnegnekini & gneguna	millet	leaves
OCT_M_30	5	3.3	F02	breakfast	monie	corn	N/A
OCT_M_31	5	3.3	F02	lunch	gnegnekini & gneguna	rice	leaves
OCT_M_32	13	8.8	F06	breakfast	serie	corn	N/A
OCT_M_33	13	8.8	F06	dinner	toh & na	corn	leaves
OCT_M_34	13	8.8	F06	lunch	gnegnekini & gneguna	corn	leaves

(continued on next page)

[a]Standard adult equivalence factors defined in terms of sex and age [Baldwin 1987, Joseph 1990]. Children 0-14 years (0.5); adult women 14-59 years (0.8); adult men 14-59 years (1.0); elders 59 years and above (0.8).

Table L.1. (continued) Observational Cooking Test data for cooking meals.

Test ID	Cookstove type	No. fires	Pot sizes (kg)
OCT_M_01	low thermal capacity	1	No. 4 (1.134), No. 2 (0.717)
OCT_M_02	three-stone fire	1	No. 5 (2.532)
OCT_M_03	three-stone fire	1	No. 5 (2.523), No. 2 (1.073)
OCT_M_04	three-stone fire	1	No. 4 (1.608), No. 2 (1.073)
OCT_M_05	three-stone fire	1	No. 4 (1.633)
OCT_M_06	three-stone fire	1	No. 4 (1.598), No. 2 (1.063)
OCT_M_07	hand-crafted metal	1	No. 5 (1.962)
OCT_M_08	hand-crafted metal	1	No. 5 (2.213), No. 2 (1.277)
OCT_M_09	hand-crafted metal	1	No. 5 (2.310), No. 2 (1.345)
OCT_M_10	manufactured metal	1	No. 4 (1.787)
OCT_M_11	gakourouwana	2[b]	No. 4 (1.746), No. 2 (1.118)
OCT_M_12	gakourouwana	2[c]	No. 4 (1.770), No. 2 (0.811)
OCT_M_13	manufactured metal	1	No. 5 (1.834)
OCT_M_14	three-stone fire	1	No. 4 (1.430)
OCT_M_15	three-stone fire	1	No. 4 (1.450), No. 2 (0.930)
OCT_M_16	three-stone fire	1	No. 4 (1.450)
OCT_M_17	three-stone fire	1	No. 2 (1.170)
OCT_M_18	three-stone fire	2[c]	No. 4 (1.530), No. 2 (0.845)
OCT_M_19	hand-crafted metal	1	No. 5 (2.215)
OCT_M_20	multiple	2[c]	No. 6 (3.260), No. 4 (1.490)
OCT_M_21	hand-crafted metal	1	No. 5 (1.980), No. 2 (1.340)
OCT_M_22	multiple	2[c]	No. 6 (3.360), No. 5 (2.075)
OCT_M_23	multiple	2[c]	No. 5 (2.200), No. 2 (1.275)
OCT_M_24	multiple	2[c]	No. 4 (1.495), No. 4 (1.340)
OCT_M_25	gakourouwana	1	No. 4 (1.650)
OCT_M_26	gakourouwana	2[c]	No. 4 (1.650), No. 2 (1.135)
OCT_M_27	gakourouwana	1	No. 4 (1.755)
OCT_M_28	low thermal capacity	1	No. 2 (1.215)
OCT_M_29	low thermal capacity	2[c]	No. 1 (0.820), No. 1 (0.820)
OCT_M_30	low thermal capacity	1	No. 2 (1.135)
OCT_M_31	low thermal capacity	2[c]	No. 2 (1.135), No. 1 (0.785)
OCT_M_32	gakourouwana	1	No. 5 (1.925)
OCT_M_33	gakourouwana	2[c]	No. 5 (1.875), No. 2 (0.820)
OCT_M_34	gakourouwana	2[c]	No. 5 (1.960), No. 4 (1.560)

(continued on next page)

[b]Two fires in parallel.
[c]Two fires in sequence.

Table L.1. (continued) Observational Cooking Test data for cooking meals.

Test ID	Meal mass (kg)		Initial meal mass by component (kg)		
	Initial	Final	Porridge	Sauce	Couscous
OCT_M_01	1.252	1.735[d]	0.000	0.000	1.252
OCT_M_02	13.280	11.452	13.280	0.000	0.000
OCT_M_03	14.986	12.601	9.914	5.072	0.000
OCT_M_04	13.691	10.789	10.747	2.944	0.000
OCT_M_05	8.759	6.799	8.759	0.000	0.000
OCT_M_06	11.396	10.302	7.689	3.707	0.000
OCT_M_07	11.383	9.830	11.383	0.000	0.000
OCT_M_08	18.486	17.122	12.410	6.076	0.000
OCT_M_09	16.723	15.426	13.994	2.729	0.000
OCT_M_10	5.663	4.900	5.663	0.000	0.000
OCT_M_11	11.913	10.968	7.957	3.956	0.000
OCT_M_12	8.284	7.691	5.929	2.355	0.000
OCT_M_13	8.729	7.856	8.729	0.000	0.000
OCT_M_14	6.775	5.810	6.775	0.000	0.000
OCT_M_15	10.700	9.150	6.380	4.320	0.000
OCT_M_16	2.415	3.675[d]	0.000	0.000	2.415
OCT_M_17	4.095	3.685	4.095	0.000	0.000
OCT_M_18	9.180	7.780	6.315	2.865	0.000
OCT_M_19	11.125	10.585	11.125	0.000	0.000
OCT_M_20	26.065	23.755	20.335	5.730	0.000
OCT_M_21	7.945	6.535	5.585	2.360	0.000
OCT_M_22	24.680	20.720	18.115	6.565	0.000
OCT_M_23	17.490	0.000[e]	10.740	6.750	0.000
OCT_M_24	12.235	0.000[e]	8.675	3.560	0.000
OCT_M_25	5.250	4.535	5.250	0.000	0.000
OCT_M_26	11.490	0.000[e]	9.135	2.355	0.000
OCT_M_27	1.965	0.000[e]	0.000	0.000	1.965
OCT_M_28	2.785	0.000[e]	2.785	0.000	0.000
OCT_M_29	6.050	0.000[e]	4.280	1.770	0.000
OCT_M_30	1.755	1.345	1.755	0.000	0.000
OCT_M_31	7.250	0.000[e]	5.780	1.470	0.000
OCT_M_32	4.760	0.000[e]	4.760	0.000	0.000
OCT_M_33	6.510	0.000[e]	4.410	2.100	0.000
OCT_M_34	10.775	0.000[e]	6.240	4.535	0.000

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[d]Couscous is steamed, steamed grains increases final mass above the initial mass.
[e]Missing data point.

Table L.1. (continued) Observational Cooking Test data for cooking meals.

Test ID	Dry ingredient mass (kg)				Water mass (kg)		
	Total	Porridge	Sauce	Couscous	Total	Porridge	Sauce
OCT_M_01	1.252	0.000	0.000	1.252	0.000	0.000	0.000
OCT_M_02	2.333	2.333	0.000	0.000	10.947	10.947	0.000
OCT_M_03	3.539	1.924	1.615	0.000	11.447	7.990	3.457
OCT_M_04	2.406	1.891	0.515	0.000	11.285	8.856	2.429
OCT_M_05	1.194	1.194	0.000	0.000	7.565	7.565	0.000
OCT_M_06	2.208	1.691	0.517	0.000	9.188	5.998	3.190
OCT_M_07	1.492	1.492	0.000	0.000	9.891	9.891	0.000
OCT_M_08	4.834	3.008	1.826	0.000	13.652	9.402	4.250
OCT_M_09	3.660	3.370	0.290	0.000	13.063	10.624	2.439
OCT_M_10	0.968	0.968	0.000	0.000	4.695	4.695	0.000
OCT_M_11	3.636	1.909	1.727	0.000	8.277	6.048	2.229
OCT_M_12	1.880	1.460	0.420	0.000	6.404	4.469	1.935
OCT_M_13	1.538	1.538	0.000	0.000	7.191	7.191	0.000
OCT_M_14	0.910	0.910	0.000	0.000	5.865	5.865	0.000
OCT_M_15	2.415	1.480	0.935	0.000	8.285	4.900	3.385
OCT_M_16	2.415	0.000	0.000	2.415	0.000	0.000	0.000
OCT_M_17	0.460	0.460	0.000	0.000	3.635	3.635	0.000
OCT_M_18	1.680	1.360	0.320	0.000	7.500	4.955	2.545
OCT_M_19	1.515	1.515	0.000	0.000	9.610	9.610	0.000
OCT_M_20	7.695	5.515	2.180	0.000	18.370	14.820	3.550
OCT_M_21	1.895	1.560	0.335	0.000	6.050	4.025	2.025
OCT_M_22	6.780	4.340	2.440	0.000	17.900	13.775	4.125
OCT_M_23	4.170	2.490	1.680	0.000	13.320	8.250	5.070
OCT_M_24	2.650	2.110	0.540	0.000	9.585	6.565	3.020
OCT_M_25	0.829	0.829	0.000	0.000	4.421	4.421	0.000
OCT_M_26	3.388	2.348	1.040	0.000	8.102	6.787	1.315
OCT_M_27	1.965	0.000	0.000	1.965	0.000	0.000	0.000
OCT_M_28	0.395	0.395	0.000	0.000	2.390	2.390	0.000
OCT_M_29	1.685	0.970	0.715	0.000	4.365	3.310	1.055
OCT_M_30	0.325	0.325	0.000	0.000	1.430	1.430	0.000
OCT_M_31	1.685	1.135	0.550	0.000	5.565	4.645	0.920
OCT_M_32	0.780	0.780	0.000	0.000	3.980	3.980	0.000
OCT_M_33	1.705	1.170	0.535	0.000	4.805	3.240	1.565
OCT_M_34	3.400	1.375	2.025	0.000	7.375	4.865	2.510

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Table L.1. (continued) Observational Cooking Test data for cooking meals.

Test ID	Grain mass (kg)		Other ingredient mass (kg)			Percentage dry ingredients (%)		
	Porridge	Couscous	Leaves	Peanuts	Other	Total	Grain	Other
OCT_M_01	0.000	0.822	0.430	0.000	0.000	1.000	0.657	0.343
OCT_M_02	2.333	0.000	0.000	0.000	0.000	0.176	0.176	0.000
OCT_M_03	1.924	0.000	1.044	0.486	0.085	0.236	0.128	0.108
OCT_M_04	1.891	0.000	0.415	0.000	0.100	0.176	0.138	0.038
OCT_M_05	1.194	0.000	0.000	0.000	0.000	0.136	0.136	0.000
OCT_M_06	1.691	0.000	0.000	0.517	0.000	0.194	0.148	0.045
OCT_M_07	1.492	0.000	0.000	0.000	0.000	0.131	0.131	0.000
OCT_M_08	3.008	0.000	0.995	0.636	0.195	0.261	0.163	0.099
OCT_M_09	3.370	0.000	0.290	0.000	0.000	0.219	0.202	0.017
OCT_M_10	0.968	0.000	0.000	0.000	0.000	0.171	0.171	0.000
OCT_M_11	1.909	0.000	1.282	0.445	0.000	0.305	0.160	0.145
OCT_M_12	1.460	0.000	0.315	0.000	0.105	0.227	0.176	0.051
OCT_M_13	1.538	0.000	0.000	0.000	0.000	0.176	0.176	0.000
OCT_M_14	0.910	0.000	0.000	0.000	0.000	0.134	0.134	0.000
OCT_M_15	1.480	0.000	0.560	0.265	0.110	0.226	0.138	0.087
OCT_M_16	0.000	1.310	0.915	0.000	0.190	1.000	0.542	0.458
OCT_M_17	0.460	0.000	0.000	0.000	0.000	0.112	0.112	0.000
OCT_M_18	1.360	0.000	0.000	0.220	0.100	0.183	0.148	0.035
OCT_M_19	1.515	0.000	0.000	0.000	0.000	0.136	0.136	0.000
OCT_M_20	5.515	0.000	1.245	0.495	0.440	0.295	0.212	0.084
OCT_M_21	1.560	0.000	0.165	0.000	0.170	0.239	0.196	0.042
OCT_M_22	4.340	0.000	1.445	0.530	0.465	0.275	0.176	0.099
OCT_M_23	2.490	0.000	1.015	0.470	0.195	0.238	0.142	0.096
OCT_M_24	2.110	0.000	0.000	0.355	0.185	0.217	0.172	0.044
OCT_M_25	0.829	0.000	0.000	0.000	0.000	0.158	0.158	0.000
OCT_M_26	2.348	0.000	0.460	0.290	0.290	0.295	0.204	0.091
OCT_M_27	0.000	1.600	0.365	0.000	0.000	1.000	0.814	0.186
OCT_M_28	0.395	0.000	0.000	0.000	0.000	0.142	0.142	0.000
OCT_M_29	0.970	0.000	0.410	0.225	0.080	0.279	0.160	0.118
OCT_M_30	0.325	0.000	0.000	0.000	0.000	0.185	0.185	0.000
OCT_M_31	1.135	0.000	0.295	0.000	0.255	0.232	0.157	0.076
OCT_M_32	0.780	0.000	0.000	0.000	0.000	0.164	0.164	0.000
OCT_M_33	1.170	0.000	0.370	0.000	0.165	0.262	0.180	0.082
OCT_M_34	1.375	0.000	1.285	0.415	0.325	0.316	0.128	0.188

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Table L.1. (continued) Observational Cooking Test data for cooking meals.

Test ID	Wood name	Mass, as-received (kg)	Moisture content, as-received (wt%)	Ignition method	Mass change in char, as-received (kg)	Energy use (MJ)		
						Total, includes char	Total, excludes char	Char unused
OCT_M_01	gendu	1.833	10.45	plastic	0.173	27.969	22.795	5.174
OCT_M_02	damba	2.241	11.15	char	0.131	32.562	28.644	3.918
OCT_M_03	damba	5.215	11.15	straw	0.198	74.147	68.225	5.922
OCT_M_04	damba	2.134	11.15	char	0.129	30.341	26.483	3.858
OCT_M_05	gendu	2.696	10.95	straw	0.318	40.874	31.362	9.511
OCT_M_06	gendu	3.158	10.95	straw	0.251	47.878	40.370	7.507
OCT_M_07	gendu	2.663	11.30	straw	0.320	40.186	30.615	9.571
OCT_M_08	gendu	2.757	11.30	char	0.244	41.605	34.307	7.298
OCT_M_09	gendu	3.037	11.30	char	0.231	45.830	38.921	6.909
OCT_M_10	tamba	1.631	10.58	plastic	0.385	26.217	14.702	11.515
OCT_M_11	tamba	4.425	10.58	straw	0.318	71.129	61.617	9.511
OCT_M_12	tamba	1.861	10.67	plastic	0.356	29.471	18.823	10.648
OCT_M_13	gendu	0.934	10.95	char	0.135	14.160	10.122	4.038
OCT_M_14	gendu	1.963	15.60	char	0.190	27.955	22.272	5.683
OCT_M_15	gendu	2.470	15.60	char	0.170	35.175	30.090	5.085
OCT_M_16	gendu	2.033	15.60	char	0.219	28.952	22.401	6.550
OCT_M_17	gendu	2.288	43.11	char	0.070	20.143	18.049	2.094
OCT_M_18	gendu	2.940	43.11	char	0.080	25.883	23.490	2.393
OCT_M_19	tamba	2.005	28.65	straw	0.210	24.727	18.446	6.281
OCT_M_20	barra	5.939	20.01	char	0.655	78.462	58.871	19.591
OCT_M_21	tamba	3.825	28.65	straw	0.230	47.173	40.294	6.879
OCT_M_22	gendu	4.820	15.60	char	0.705	68.641	47.554	21.087
OCT_M_23	damba	3.335	19.09	char	0.110	43.254	39.964	3.290
OCT_M_24	barra	3.280	15.46	char	0.130	44.816	40.928	3.888
OCT_M_25	jalla	1.670	13.96	plastic	0.210	26.122	19.841	6.281
OCT_M_26	jalla	2.035	13.96	straw	0.205	31.832	25.700	6.132
OCT_M_27	jalla	1.870	13.96	char	0.140	29.251	25.063	4.187
OCT_M_28	damba	1.650	13.96	char	0.105	22.590	19.450	3.141
OCT_M_29	gendu	2.570	13.96	char	0.130	37.432	33.543	3.889
OCT_M_30	tamba	1.285	14.03	straw	0.055	19.739	18.094	1.645
OCT_M_31	damba	3.620	14.22	char	0.090	49.385	46.694	2.691
OCT_M_32	gendu	1.415	13.62	char	0.195	20.704	14.871	5.832
OCT_M_33	gendu	1.790	13.62	char	0.080	26.191	23.798	2.393
OCT_M_34	gendu	2.820	13.62	char	0.145	41.261	36.924	4.337

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Table L.1. (continued) Observational Cooking Test data for cooking meals.

Test ID	Time (min)	Firepower[f] (kW)	Season	Air temp. (°C)
OCT_M_01	85	4.5	dry and hot	35.0
OCT_M_02	45	10.6	dry and hot	29.8
OCT_M_03	109	10.4	dry and hot	31.5
OCT_M_04	61	7.2	dry and hot	35.0
OCT_M_05	38	13.8	dry and hot	31.0
OCT_M_06	84	8.0	dry and hot	32.0
OCT_M_07	104	4.9	dry and hot	30.0
OCT_M_08	74	7.7	dry and hot	34.5
OCT_M_09	95	6.8	dry and hot	39.5
OCT_M_10	53	4.6	dry and hot	29.5
OCT_M_11	52	19.7[g]	dry and hot	32.5
OCT_M_12	93	3.4	dry and hot	35.3
OCT_M_13	55	3.1	dry and hot	28.2
OCT_M_14	57	6.5	temperate and rainy	25.0
OCT_M_15	90	5.6	temperate and rainy	26.7
OCT_M_16	80	4.7	temperate and rainy	27.0
OCT_M_17	60	5.0	temperate and rainy	25.3
OCT_M_18	184	2.1	temperate and rainy	23.2
OCT_M_19	59	5.2	temperate and rainy	24.9
OCT_M_20	117	8.4	temperate and rainy	25.3
OCT_M_21	107	6.3	temperate and rainy	26.6
OCT_M_22	105	7.5	temperate and rainy	28.3
OCT_M_23	97	6.9	temperate and rainy	28.8
OCT_M_24	87	7.8	temperate and rainy	26.8
OCT_M_25	44	7.5	temperate and rainy	24.9
OCT_M_26	123	3.5	temperate and rainy	28.0
OCT_M_27	50	8.4	temperate and rainy	31.8
OCT_M_28	61	5.3	temperate and rainy	21.2
OCT_M_29	107	5.2	temperate and rainy	22.4
OCT_M_30	58	5.2	temperate and rainy	23.2
OCT_M_31	110	7.1	temperate and rainy	29.0
OCT_M_32	38	6.5	temperate and rainy	25.0
OCT_M_33	96	4.1	temperate and rainy	27.8
OCT_M_34	102	6.0	temperate and rainy	25.9

[f]Approximate firepower calculated over the cooking event from total energy use excluding char energy.
[g]Combined firepower of two active fires in parallel.

Table L.2. Example time-series data for cooking a meal.

Cooking test ID: OCT_M_15	Cookstove: three-stone fire
Time of day: lunch	No. fires: one
Meal: gnegnikini (porridge) & gneguna (sauce)	Pot 1: sauce (leaves)
Location: indoor kitchen	Pot 2: grains (corn)
Cooking time (min): 90	

Time (hh:mm)	Activity
8:43	start fire with burning char embers
	add pot 1 to fire with water
	add lid to pot 1
8:44-9:01	cook outside of kitchen cutting leaves for sauce
8:48	return briefly to tend fire (rearrange wood)
	fan fire
9:01	check pot 1
	tend fire and fan fire
9:07	remove lid on pot 1
	add leaves to pot 1
	tend fire
9:07-9:21	cook left compound to get water
9:21	tend fire
	add chicken bouillon to pot 1
	add peanut butter to pot 1
	add salt to pot 1
	stir pot 1
9:26	stir pot 1
9:28	tend fire
9:32	remove pot 1 and place aside on warming three-stone fire
	remove 1/4 of sticks to warm pot 1
	add pot 2 to fire with water
	add lid to pot 2
	tend fire
9:34	add local spice to pot 1
	add okra power to pot 1
9:34-9:36	stir pot 1

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Table L.2. (continued) Example time-series data for cooking a meal.

Time (hh:mm)	Activity
9:51	tend fire
9:53	check pot 2
	tend fire
9:57	remove lid on pot 2
	add grains to pot 2
	stir pot 2
10:02	stir pot 2
	add lid to pot 2
10:05	tend fire
10:07	remove 1/2 of remaining sticks from fire
10:13	remove pot 2 from fire
	remove pot 1 from warming fire
	end

Table L.3. Observational Cooking Test data for heating water.

Test ID	Number of people	Std. adult equiv.[a]	Family ID	Cookstove type	Pot sizes (kg)	Water mass (kg)	Wood name	Mass, as-received (kg)	Moisture content, as-received (wt%)
OCT_W_01	12	8.4	F03	three-stone fire	No. 6 (3.045)	98.390	barra	4.43	15.46
OCT_W_02	12	8.5	F01	three-stone fire	No. 6 (2.920)	62.265	tamba	2.095	15.60
OCT_W_03	5	3.3	F02	gakourouwana	No. 5 (2.215)	23.260	jalla	1.585	13.96

Test ID	Ignition method	Mass change in char, as-received (kg)	Energy (MJ)			Time (min)	Firepower[b] (kW)	Air temp. (°C)
			Total, includes char	Total, excludes char	Char unused			
OCT_W_01	char	0.050	62.037	60.541	1.496	101	10.0	26.8
OCT_W_02	straw	0.000	31.498	31.498	0.000	200	2.6	28.0
OCT_W_03	plastic	0.185	24.793	19.259	5.533	48	6.7	31.8

[a]Standard adult equivalence factors defined in terms of sex and age [Baldwin 1987, Joseph 1990]. Children 0-14 years (0.5); adult women 14-59 years (0.8); adult men 14-59 years (1.0); elders 59 years and above (0.8).
[b]Approximate firepower calculated over the cooking event from total energy use excluding char energy.

Notes:

- All tests completed on one fire.
- All tests completed in the evening.
- All tests completed in the temperate and rainy season.

Table L.4. Example time-series data for heating water.

Cooking test ID: OCT_W_01	Cookstove: three-stone fire
Time of day: evening	No. fires: one
Location: outdoors	
Cooking time (min): 101	One bowl holds ~2.730 kg water

Time (hh:mm)	Activity	Water temp. in pot (°C)
17:44	start fire with burning char embers	
17:47	add pot with 19.8 kg water	28.5
	tend fire	
17:55	tend fire	
	fan fire	
18:10	tend fire	
18:15	remove 4 bowls water from pot	50.5
	add 4 bowls water to pot	
18:16		42.5
18:19	remove 4 bowls water from pot	44.0
18:21	remove 3 bowls water from pot	
18:22	add 8 bowls water to pot	
18:25		37.5
18:30	tend fire	
18:36	take 8 bowls water from pot	48.3
	add 6 bowls water to pot	
18:47	take 7 bowls water from pot	49.5
	add 7 bowls water to pot	
18:48		32.0
18:55	tend fire	
19:06		52.6
19:08	take 7 bowls water from pot	
	add 3 bowls water to pot	
19:09		42.2
19:25	remove 3 bowls water from pot	67.5
	end	

Comments:

1. Cook is constantly refilling a pale of water in nearby well when not at fire.
2. Cook mixes warm water from cooking pot with cool water from well.
3. Cool and hot water mixed to appropriate temperature for each individual.

Table L.5. Bathing water temperatures for members in a family.

Age	Gender (M/F)	Temp (°C)
10	M	40.0
7	F	42.5
3	F	42.5
15	M	39.3
50	M	48.3
8	F	45.4
9	M	44.5
29	F	42.6
25	F	47.2
39	M	44.7
17	F	45.9
8	F	41.3

Test ID: OCT_W_1

Number people: 12

Mean: 43.7 °C

σ: 2.8°C

Table L.6. Observational Cooking Test data for roasting peanuts.

Test ID	Number of people	Std. adult equiv.[a]	Family ID	Time of day	Pot size (kg)	Peanut mass (kg)	Wood name	Mass, as-received (kg)	Moisture content, as-received (wt%)
OCT_P_01	17	10.7	F12	afternoon	No. 7 (3.565)	1.600	damba	0.824	12.85
OCT_P_02	12	8.4	F50	morning	No. 6 (2.965)	11.700	damba	3.934	7.84
OCT_P_03	23	14.5	F10	morning	No. 4 (2.835)	3.160	tamba	1.378	6.54
OCT_P_04	7	4.3	F56	morning	No. 4 (1.650)	1.420	barra	1.068	7.09

Test ID	Ignition method	Mass change in char, as-received (kg)	Energy use (MJ)			Time (min)	Firepower[b] (kW)	Air temp. (°C)
			Total, includes char	Total, excludes char	Char unused			
OCT_P_01	straw	0.100	11.453	8.462	2.991	29	4.863	28.8
OCT_P_02	char	0.190	58.375	52.692	5.683	114	7.703	18.1
OCT_P_03	char	0.200	23.303	17.321	5.982	43	6.714	23.2
OCT_P_04	straw	0.126	16.695	12.926	3.769	40	5.386	22.0

[a]Standard adult equivalence factors defined in terms of sex and age [Baldwin 1987, Joseph 1990]. Children 0-14 years (0.5); adult women 14-59 years (0.8); adult men 14-59 years (1.0); elders 59 years and above (0.8).
[b]Approximate firepower calculated over the cooking event from total energy use excluding char energy.

Notes:

- All tests completed on a three-stone fire.
- All tests completed on one fire.
- All tests completed in the cold and dry season.

Table L.7. Example time-series data for roasting peanuts.

Cooking test ID: OCT_P_01 Time of day: afternoon Location: outdoors Cooking time (min): 29	Cookstove: three-stone fire No. fires: one

Time (hh:mm)	Activity
15:33	start fire with straw and lighter
	add 1.6 kg peanuts to pot
	add 0.1 kg corn sheaths to pot
15:33-16:02	constantly stir peanuts and corn sheaths
15:40	tend fire
15:52	tend fire
16:02	remove pot
	end

Comments:

1. Corn sheaths added to distribute heat between peanuts. Sand can also be used.
2. Pot is held between rocks at approximately 30° tilt from horizontal.
3. Tipped pot forces peanuts to bunch together in slopped edge of pot and not spread out thin along bottom of pot.
4. Tipped pot also makes stirring easier.

Table L.8. Observational Cooking Test data for making medicine.

Test ID	Family ID	Ailment (malaria)		Time of day	Pot size (kg)	Medicine name	Initial mass (kg)			Final mass (kg)
		Medicinal intent	Number of people				Water	Leaf	Total	
OCT_M_01	F12	treatment	1	evening	No. 7 (2.240)	Barra Woule (red)	5.065	0.380	5.445	4.840
OCT_M_02	F12	prevention	8	morning	No. 6 (2.965)	Djon Boulou	5.310	0.700	6.010	4.850
OCT_M_03	F56	treatment	1	morning	No. 4 (1.445)	Barra Woule (red)	4.050	0.400	4.450	3.690

Test ID	Wood name	Mass, as-received (kg)	Moisture content, as-received (wt%)	Ignition method	Mass change in char, as-received (kg)	Energy use (MJ)			Time (min)	Firepower[a] (kW)	Air temp. (°C)
						Total, includes char	Total, excludes char	Char unused			
OCT_M_01	damba	0.650	12.85	char	0.010	9.035	8.735	0.299	42	3.5	35.5
OCT_M_02	damba	1.680	7.84	straw	0.120	24.929	21.340	3.589	51	7.0	34.0
OCT_M_03	barra	1.335	7.09	char	0.145	20.868	16.531	4.337	41	6.7	28.6

[a]Approximate firepower calculated over the cooking event from total energy use excluding char energy.

Notes:

- All tests completed on a three-stone fire.
- All tests completed on one fire.
- All tests completed in the cold and dry season.

Table L.9. Example time-series data for making medicine.

Cooking test ID: OCT_M_01 Time of day: afternoon Location: indoors Cooking time (min): 42	Cookstove: three-stone fire No. fires: one

Time (hh:mm)	Activity
16:31	start fire with burning char embers
	add 5.065 kg water to pot
	add 0.380 kg medicinal leaves to pot
	add pot to fire
	place lid on pot
16:40	tend fire
16:52	tend fire
17:13	remove pot from fire
	end

Table L.10. Observational Cooking Test data for steeping tea.

Test ID	Family ID	Time of day	Pot size (kg)	Initial mass of ingredients (kg)[a]		
				Tea leaves	Sugar	Water
OCT_T_01	F01	evening	0.190	0.020	0.150	0.779
OCT_T_02	F10	morning	0.182	0.025	0.135	0.789
OCT_T_03	F12	afternoon	0.185	0.025	0.195	0.850

Test ID	Mass char (kg)	Moisture content, as-received (wt%)	Energy use (MJ)	Time (min)	Firepower[b] (kW)	Season	Air temp. (°C)
OCT_T_01	0.044	1.75	1.306	70	0.31	hot and dry	36.0
OCT_T_02	0.050	1.75	1.484	56	0.44	cold and dry	26.0
OCT_T_03	0.065	1.75	1.929	71	0.45	cold and dry	36.0

[a]Tea is steeped three times, water and sugar are split approximately evenly between each steep whereas the tea leaves are used in each steep.
[b]Approximate firepower calculated over the cooking event from total energy use excluding char energy.

Notes:

- All tests completed on a tea charcoal stove.
- All tests completed on one fire.
- All tests completed using charcoal for fuel.
- All fires ignited by burning charcoal embers taken from another fire.

Table L.11. Example time-series data for steeping tea.

Cooking test ID: OCT_T_01 Time of day: afternoon Location: indoors Cooking time (min): 70	Cookstove: tea charcoal stove No. fires: one

Time (hh:mm)	Activity
16:44	start fire
	add 20 g tea leaves to teapot 1
	add 239 g water to teapot 1
	place teapot 1 on fire
16:57	remove teapot 1 from stove and taste tea
	place teapot 1 on fire
16:59	add 50 g sugar to teapot 2
17:02	remove teapot 1 from stove and taste tea
	pour tea from teapot 1 into teapot 2
17:04	add 260 g water to teapot 1
	place teapot 1 on fire
17:05-17:08	pour tea from teapot 2 into glass, and back, to create froth
17:08-17:14	go outside kitchen to serve tea from teapot 2
17:28	remove teapot 1 from stove and taste tea
	add 50 g sugar to teapot 2
	pour tea from teapot 1 into teapot 2
17:29	shake stove to clear ash from char
	add 280 g water to teapot 1
	place teapot 1 on fire
17:30-17:32	pour tea from teapot 2 into glass, and back, to create froth
17:32	remove teapot 1 from fire
	place teapot 2 on fire (to warm up for serving)
17:34	remove teapot 2 from fire
	place teapot 1 on fire
17:34-17:45	go outside kitchen to serve tea from teapot 2
17:49	remove teapot 1 from stove and taste tea
	shake stove to clear ash from char
	return teapot 1 on fire

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Table L.11. (continued) Example time-series data for steeping tea.

Time (hh:mm)	Activity
17:51	add 50 g sugar to teapot 2
	pour tea from teapot 1 into teapot 2
17:52-17:54	pour tea from teapot 2 into glass, and back, to create froth
17:54	go outside kitchen to serve tea from teapot 2
	end

Comments:

Need two teapots; one to hold tea leaves and another for mixing tea with sugar.

APPENDIX M

SESSION COOKING TEST

Date		Head male		Family ID	
Time		Cook		No. eating	
Cooking application		Ignition method		Cooking Location	
Ambient temp (C)		Cookstove type(s)		Cooking order	sequence OR parallel

Fuel type and name	Start (kg)	End (kg)	Used (kg)	Pot No(s).

Pot No.	Pot size and mass (kg)	Cooking description

Ingredient	Pot (kg)	Pot with ingred. (kg)	Ingred. (kg)	Pot No.?	Comments (e.g., coarse ground flour)

Total mass	Start (kg)	End (kg)	Diff (kg)
Pot 1			
Pot 2			

Additional comments

Table M.1. Session Cooking Test data for cooking meals.

Test ID	Number of people	Stand. adult equiv.[a]	Family ID	Meal time of day	Meal type	Grain type	Sauce type
SCT_M_01	13	8.8	F06	breakfast	serie	millet	N/A
SCT_M_02	15	10.8	F06	dinner	couscous	millet	N/A
SCT_M_03	23	14.5	F10	breakfast	monie	millet	N/A
SCT_M_04	6	3.8	F11	breakfast	monie	millet	N/A
SCT_M_05	5	3.6	F21	breakfast	serie	millet	N/A
SCT_M_06	7	4.6	F19	breakfast	serie	millet	N/A
SCT_M_07	7	4.6	F19	lunch	gnegnekini & gneguna	millet	peanut
SCT_M_08	7	4.6	F19	dinner	couscous	millet	N/A
SCT_M_09	10	6.8	F32	breakfast	monie	millet	N/A
SCT_M_10	10	6.8	F32	lunch	gnegnekini & gneguna	millet	leaves
SCT_M_11	8	4.8	F32	dinner	gnegnekini & gneguna	millet	peanut
SCT_M_12	9	6.1	F35	breakfast	monie	corn	N/A
SCT_M_13	9	6.1	F35	dinner	gnegnekini & gneguna	millet	leaves
SCT_M_14	21	12.8	F24	breakfast	serie	millet	N/A
SCT_M_15	3	2.3	F36	lunch	gnegnekini & gneguna	rice	leaves
SCT_M_16	7	4.3	F18	breakfast	monie	corn	N/A
SCT_M_17	7	4.3	F18	dinner	toh & na	corn	other
SCT_M_18	20	12.8	F03	lunch	gnegnekini & gneguna	millet	leaves
SCT_M_19	20	12.8	F03	dinner	toh & na	millet	leaves
SCT_M_20	12	7.4	F06	lunch	gnegnekini & gneguna	corn	leaves
SCT_M_21	12	7.4	F06	dinner	gnegnekini & gneguna	millet	peanut
SCT_M_22	12	7.4	F06	lunch	gnegnekini & gneguna	millet	peanut
SCT_M_23	20	12.8	F03	dinner	toh & na	millet	other
SCT_M_24	10	7.5	F10	breakfast	serie	corn	N/A

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[a]Standard adult equivalence factors defined in terms of sex and age [Baldwin 1987, Joseph 1990]. Children 0-14 years (0.5); adult women 14-59 years (0.8); adult men 14-59 years (1.0); elders 59 years and above (0.8).

Table M.1. (continued) Session Cooking Test data for cooking meals.

Test ID	Cookstove type	No. fires	Initial meal mass (kg)	Meal mass by component (kg)		
				Porridge	Sauce	Couscous
SCT_M_01	low thermal capacity	1	5.085	5.085	0.000	0.000
SCT_M_02	low thermal capacity	1	3.520	0.000	0.000	3.520
SCT_M_03	three-stone fire	1	8.990	8.990	0.000	0.000
SCT_M_04	manufactured metal	1	3.830	3.830	0.000	0.000
SCT_M_05	manufactured metal	1	3.800	3.800	0.000	0.000
SCT_M_06	gakourouwana	1	6.430	6.430	0.000	0.000
SCT_M_07	gakourouwana	2	9.150	6.815	2.335	0.000
SCT_M_08	gakourouwana	1	1.520	0.000	0.000	1.520
SCT_M_09	three-stone fire	1	3.800	3.800	0.000	0.000
SCT_M_10	three-stone fire	2	7.245	4.715	2.530	0.000
SCT_M_11	three-stone fire	2	5.225	4.030	1.195	0.000
SCT_M_12	three-stone fire	1	5.230	5.230	0.000	0.000
SCT_M_13	three-stone fire	2	10.770	6.500	4.270	0.000
SCT_M_14	three-stone fire	1	7.690	7.690	0.000	0.000
SCT_M_15	hand-crafted metal	1	3.870	2.665	1.205	0.000
SCT_M_16	gakourouwana	1	3.850	3.850	0.000	0.000
SCT_M_17	gakourouwana	2	4.050	2.845	1.205	0.000
SCT_M_18	multiple	2	15.605	10.260	5.345	0.000
SCT_M_19	hand-crafted metal	2	12.540	9.935	2.605	0.000
SCT_M_20	gakourouwana	1	13.000	9.765	3.235	0.000
SCT_M_21	gakourouwana	1	11.450	8.480	2.970	0.000
SCT_M_22	three-stone fire	2	8.040	5.435	2.605	0.000
SCT_M_23	three-stone fire	2	11.215	8.030	3.185	0.000
SCT_M_24	gakourouwana	1	6.815	6.815	0.000	0.000

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Table M.1. (continued) Session Cooking Test data for cooking meals.

Test ID	Dry ingredient mass (kg)				Water mass (kg)		
	Total	Porridge	Sauce	Couscous	Total	Porridge	Sauce
SCT_M_01	0.750	0.750	0.000	0.000	4.335	4.335	0.000
SCT_M_02	3.520	0.000	0.000	3.520	0.000	0.000	0.000
SCT_M_03	1.200	1.200	0.000	0.000	7.790	7.790	0.000
SCT_M_04	0.595	0.595	0.000	0.000	3.235	3.235	0.000
SCT_M_05	0.495	0.495	0.000	0.000	3.305	3.305	0.000
SCT_M_06	0.625	0.625	0.000	0.000	5.805	5.805	0.000
SCT_M_07	2.510	1.760	0.750	0.000	6.640	5.055	1.585
SCT_M_08	1.520	0.000	0.000	1.520	0.000	0.000	0.000
SCT_M_09	1.020	1.020	0.000	0.000	2.780	2.780	0.000
SCT_M_10	2.155	1.125	1.030	0.000	5.090	3.590	1.500
SCT_M_11	1.545	1.150	0.395	0.000	3.680	2.880	0.800
SCT_M_12	1.115	1.115	0.000	0.000	4.115	4.115	0.000
SCT_M_13	2.030	1.255	0.775	0.000	8.740	5.245	3.495
SCT_M_14	1.400	1.400	0.000	0.000	6.290	6.290	0.000
SCT_M_15	0.790	0.550	0.240	0.000	3.080	2.115	0.965
SCT_M_16	0.595	0.595	0.000	0.000	3.255	3.255	0.000
SCT_M_17	0.970	0.665	0.305	0.000	3.080	2.180	0.900
SCT_M_18	4.330	2.340	1.990	0.000	11.275	7.920	3.355
SCT_M_19	4.030	3.725	0.305	0.000	8.510	6.210	2.300
SCT_M_20	2.205	1.900	0.305	0.000	10.795	7.865	2.930
SCT_M_21	2.210	1.750	0.460	0.000	9.240	6.730	2.510
SCT_M_22	1.550	1.210	0.340	0.000	6.490	4.225	2.265
SCT_M_23	3.520	2.770	0.750	0.000	7.695	5.260	2.435
SCT_M_24	0.810	0.810	0.000	0.000	6.005	6.005	0.000

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Table M.1. (continued) Session Cooking Test data for cooking meals.

Test ID	Grain mass (kg)		Other ingredient mass (kg)			Percentage dry ingredients (%)		
	Porridge	Couscous	Leaves	Peanuts	Other	Total	Grain	Other
SCT_M_01	0.750	0.000	0.000	0.000	0.000	0.147	0.147	0.000
SCT_M_02	0.000	1.540	1.980	0.000	0.000	1.000	0.438	0.563
SCT_M_03	1.200	0.000	0.000	0.000	0.000	0.133	0.133	0.000
SCT_M_04	0.595	0.000	0.000	0.000	0.000	0.155	0.155	0.000
SCT_M_05	0.495	0.000	0.000	0.000	0.000	0.130	0.130	0.000
SCT_M_06	0.625	0.000	0.000	0.000	0.000	0.097	0.097	0.000
SCT_M_07	1.760	0.000	0.060	0.520	0.170	0.274	0.192	0.082
SCT_M_08	0.000	0.905	0.615	0.000	0.000	1.000	0.595	0.405
SCT_M_09	1.020	0.000	0.000	0.000	0.000	0.268	0.268	0.000
SCT_M_10	1.125	0.000	1.010	0.000	0.020	0.297	0.155	0.142
SCT_M_11	1.150	0.000	0.000	0.355	0.040	0.296	0.220	0.076
SCT_M_12	1.115	0.000	0.000	0.000	0.000	0.213	0.213	0.000
SCT_M_13	1.255	0.000	0.590	0.185	0.000	0.188	0.117	0.072
SCT_M_14	1.400	0.000	0.000	0.000	0.000	0.182	0.182	0.000
SCT_M_15	0.550	0.000	0.000	0.000	0.240	0.204	0.142	0.062
SCT_M_16	0.595	0.000	0.000	0.000	0.000	0.155	0.155	0.000
SCT_M_17	0.665	0.000	0.000	0.200	0.105	0.240	0.164	0.075
SCT_M_18	2.340	0.000	1.035	0.800	0.155	0.277	0.150	0.128
SCT_M_19	3.725	0.000	0.240	0.000	0.065	0.321	0.297	0.024
SCT_M_20	1.900	0.000	0.305	0.000	0.000	0.170	0.146	0.023
SCT_M_21	1.750	0.000	0.000	0.310	0.150	0.193	0.153	0.040
SCT_M_22	1.210	0.000	0.000	0.240	0.100	0.193	0.150	0.042
SCT_M_23	2.770	0.000	0.000	0.000	0.750	0.314	0.247	0.067
SCT_M_24	0.810	0.000	0.000	0.000	0.000	0.119	0.119	0.000

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Table M.1. (continued) Session Cooking Test data for cooking meals.

Test ID	Wood name	Mass, as-received (kg)	Moisture content, as-received (wt %)	Ignition method	Total energy use (MJ)	Season
SCT_M_01	tamba	1.320	13.62	char	20.387	temperate and rainy
SCT_M_02	gendu	2.525	13.62	straw	36.946	temperate and rainy
SCT_M_03	gendu	2.055	15.60	char	29.264	temperate and rainy
SCT_M_04	gendu	1.115	16.24	char	15.737	temperate and rainy
SCT_M_05	barra	0.930	14.83	char	13.137	temperate and rainy
SCT_M_06	tamba	1.480	17.80	char	21.577	temperate and rainy
SCT_M_07	tamba	4.275	17.80	plastic	62.327	temperate and rainy
SCT_M_08	gendu	0.855	17.80	char	11.804	temperate and rainy
SCT_M_09	gendu	0.745	15.18	straw	10.671	temperate and rainy
SCT_M_10	gendu	2.610	15.18	char	37.385	temperate and rainy
SCT_M_11	jalla	0.895	15.18	char	13.770	temperate and rainy
SCT_M_12	gendu	1.175	15.60	char	16.733	temperate and rainy
SCT_M_13	gendu	3.005	15.60	plastic	42.793	temperate and rainy
SCT_M_14	gendu	1.710	17.92	straw	23.568	temperate and rainy
SCT_M_15	gendu	1.735	23.50	char	21.999	temperate and rainy
SCT_M_16	gendu	0.515	15.60	char	7.334	temperate and rainy
SCT_M_17	gendu	1.355	15.60	char	19.296	temperate and rainy
SCT_M_18	gendu	4.345	15.58	char	61.893	temperate and rainy
SCT_M_19	gendu	4.315	15.58	straw	61.374	temperate and rainy
SCT_M_20	tamba	2.505	7.30	char	41.959	cold and dry
SCT_M_21	tamba	3.295	7.30	char	55.191	cold and dry
SCT_M_22	tamba	2.420	7.30	char	40.535	cold and dry
SCT_M_23	gendu	3.880	7.57	char	61.412	cold and dry
SCT_M_24	tamba	0.955	6.54	char	16.150	cold and dry

Table M.2. Session Cooking Test data for heating water.

Test ID	Number of people	Std. adult equiv.[a]	Family ID	Water mass (kg)	Wood name	Mass, as-received (kg)	Moisture content, as-received (wt %)	Ignition method	Energy use (MJ)
SCT_W_01	5	3.3	F09	20.345	gendu	1.635	13.96	char	23.814
SCT_W_02	7	4.4	F06	60.250	gendu	2.520	13.62	char	36.872
SCT_W_03	3	1.8	F10	10.680	gendu	1.375	13.96	char	20.027

[a]Standard adult equivalence factors defined in terms of sex and age [Baldwin 1987, Joseph 1990]. Children 0-14 years (0.5); adult women 14-59 years (0.8); adult men 14-59 years (1.0); elders 59 years and above (0.8).

Notes:

- The three-stone fire is used in all tests.
- Water is heated on one stove in all tests.
- Each test was completed in the evening.
- All tests completed in the temperate and rainy season.

Table M.3. Session Cooking Test data for roasting peanuts.

Test ID	Number of people	Std. adult equiv.[a]	Family ID	Peanut mass (kg)	Wood name	Mass, as-received (kg)	Moisture content, as-received (wt%)	Ignition method	Energy use (MJ)
SCT_P_01	7	4.9	F09	0.865	gendu	0.474	13.96	straw	6.904
SCT_P_02	13	9.0	F16	1.880	gendu	2.034	13.96	straw	29.625

[a]Standard adult equivalence factors defined in terms of sex and age [Baldwin 1987, Joseph 1990]. Children 0-14 years (0.5); adult women 14-59 years (0.8); adult men 14-59 years (1.0); elders 59 years and above (0.8).

Notes:

- The three-stone fire is used in all tests.
- Peanuts are roasted on one stove in all tests.
- Each test was completed in the evening.
- All tests completed in the temperate and rainy season.

Table M.4. Session Cooking Test data for boiling shea kernel.

Test ID	Family ID	Time of day	Kernel mass (kg)	Wood name	Mass, as-received (kg)	Moisture content, as-received (wt%)	Ignition method	Energy use (MJ)
SCT_BK_01	F01	morning to evening	46.025	barra	14.390	12.43	straw	209.993
SCT_BK_02	F44	morning to evening	30.085	barra	10.500	13.96	straw	150.101
SCT_BK_03	F10	morning to evening	23.630	gendu	13.880	15.55	straw	197.800

Notes:

- Shea is processed by women for income. Family size is not a factor in energy use for an individual test, only the mass heated.
- The three-stone fire is used in all tests.
- Peanuts are roasted on one stove in all tests.
- All tests completed in the temperate and rainy season.

Table M.5. Session Cooking Test data for rendering shea oil.

Test ID	Family ID	Time of day	Rendered oil mass (kg)	Wood name	Mass, as-received (kg)	Moisture content, as-received (wt%)	Ignition method	Energy use (MJ)
SCT_RO_01	F44	morning	1.890	barra	4.745	13.96	straw	67.831
SCT_RO_02	F44	morning	4.885	gendu	7.185	13.96	straw	104.648
SCT_RO_03	F26	evening	2.610	gendu	3.435	13.20	straw	50.547

Notes:

- Shea is processed by women for income. Family size is not a factor in energy use for an individual test, only the mass heated.
- The three-stone fire is used in all tests.
- Peanuts are roasted on one stove in all tests.
- All tests completed in the temperate and rainy season.

APPENDIX N

DAILY COOKING TEST

Date		Head male		Family ID	
Time		Cook		No. eating	
Cooking application		Cookstove type(s)		Cooking Location	

Fuel type and name	Start (kg)	End (kg)	Used (kg)

Cooking activity and description

Additional comments

Table N.1. Daily Cooking Test data for cooking meals.

Test ID	Number of people	Std. adult equiv.[a]	Family ID	Meal time of day	Meal type	Cookstove type	Wood name	Energy use (MJ)	Season
DCT_M_01	7	5.6	F02	breakfast	serie	three-stone fire	gendu	29.737	hot and dry
DCT_M_02	22	13.5	F01	dinner	toh & na	three-stone fire	gendu	70.721	hot and dry
DCT_M_03	17	10.9	F04	breakfast	monie	three-stone fire	krekrete	31.660	hot and dry
DCT_M_04	17	10.9	F04	lunch	gnegnekini & gneguna	three-stone fire	krekrete	48.998	hot and dry
DCT_M_05	17	10.9	F04	dinner	toh & na	three-stone fire	krekrete	52.767	hot and dry
DCT_M_06	9	6.1	F35	breakfast	serie	three-stone fire	gendu	15.162	hot and dry
DCT_M_07	9	6.1	F35	lunch	gnegnekini & gneguna	three-stone fire	gendu	43.969	hot and dry
DCT_M_08	9	6.1	F35	dinner	toh & na	three-stone fire	gendu	48.518	hot and dry
DCT_M_09	5	3.3	F02	breakfast	serie	gakourouwana	gendu	30.324	hot and dry
DCT_M_10	5	3.3	F02	lunch	steamed rice	gakourouwana	gendu	10.613	hot and dry
DCT_M_11	5	3.3	F02	dinner	other	gakourouwana	gendu	28.807	hot and dry
DCT_M_12	22	13.5	F01	breakfast	monie	three-stone fire	damba	32.792	hot and dry
DCT_M_13	22	13.5	F01	lunch	gnegnekini & gneguna	three-stone fire	damba	46.336	hot and dry
DCT_M_14	22	13.5	F01	dinner	toh & na	three-stone fire	damba	68.435	hot and dry
DCT_M_15	22	13.5	F01	breakfast	monie	three-stone fire	damba	31.366	hot and dry
DCT_M_16	22	13.5	F01	lunch	gnegnekini & gneguna	three-stone fire	damba	39.921	hot and dry
DCT_M_17	22	13.5	F01	dinner	toh & na	three-stone fire	damba	102.653	hot and dry
DCT_M_18	6	4.6	F21	breakfast	monie	three-stone fire	krekrete	36.183	hot and dry
DCT_M_19	6	4.6	F21	lunch	gnegnekini & gneguna	three-stone fire	krekrete	13.569	hot and dry
DCT_M_20	6	4.6	F21	dinner	toh & na	three-stone fire	krekrete	34.675	hot and dry
DCT_M_21	6	4.6	F21	breakfast	serie	three-stone fire	krekrete	31.660	hot and dry
DCT_M_22	6	4.6	F21	lunch	gnegnekini & gneguna	three-stone fire	krekrete	19.599	hot and dry
DCT_M_23	6	4.6	F21	dinner	toh & na	three-stone fire	krekrete	27.137	hot and dry
DCT_M_24	21	13.6	F03	breakfast	monie	three-stone fire	gendu	33.356	hot and dry
DCT_M_25	21	13.6	F03	lunch	gnegnekini & gneguna	three-stone fire	gendu	95.519	hot and dry

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Table N.1. (continued) Daily Cooking Test data for cooking meals.

Test ID	Number of people	Std. adult equiv.[a]	Family ID	Meal time of day	Meal type	Cookstove type	Wood name	Energy use (MJ)	Season
DCT_M_26	21	13.6	F03	dinner	toh & na	three-stone fire	gendu	109.165	hot and dry
DCT_M_27	21	13.6	F03	breakfast	serie	three-stone fire	gendu	45.485	hot and dry
DCT_M_28	21	13.6	F03	lunch	gnegnekini & gneguna	three-stone fire	gendu	57.615	hot and dry
DCT_M_29	21	13.6	F03	dinner	toh & na	three-stone fire	gendu	90.971	hot and dry
DCT_M_30	9	6.1	F35	lunch	gnegnekini & gneguna	low thermal capacity	gendu	46.781	temperate and rainy
DCT_M_31	13	8.8	F06	lunch	gnegnekini & gneguna	low thermal capacity	gendu	56.345	temperate and rainy
DCT_M_32	7	4.3	F18	lunch	gnegnekini & gneguna	gakourouwana	gendu	49.843	temperate and rainy
DCT_M_33	12	7.4	F07	dinner	gnegnekini & gneguna	three-stone fire	gendu	17.607	temperate and rainy
DCT_M_34	10	5.0	F10	breakfast	serie	hand-crafted metal	gendu	51.281	temperate and rainy
DCT_M_35	20	12.8	F03	breakfast	serie	hand-crafted metal	gendu	34.890	temperate and rainy
DCT_M_36	20	12.8	F03	breakfast	serie	hand-crafted metal	barra	35.401	temperate and rainy
DCT_M_37	9	6.7	F09	dinner	toh & na	three-stone fire	damba	42.821	temperate and rainy
DCT_M_38	5	3.3	F02	dinner	couscous	gakourouwana	tamba	28.069	temperate and rainy
DCT_M_39	10	6.9	F14	lunch	gnegnekini & gneguna	three-stone fire	gendu	37.026	temperate and rainy
DCT_M_40	3	2.3	F36	dinner	gnegnekini & gneguna	hand-crafted metal	gendu	18.869	temperate and rainy
DCT_M_41	20	12.8	F03	breakfast	monie	three-stone fire	gendu	55.342	cold and dry
DCT_M_42	20	12.8	F03	lunch	gnegnekini & gneguna	three-stone fire	gendu	45.064	cold and dry
DCT_M_43	20	12.8	F03	dinner	toh & na	three-stone fire	gendu	69.446	cold and dry
DCT_M_44	7	4.3	F18	breakfast	serie	gakourouwana	gendu	11.622	cold and dry
DCT_M_45	7	4.3	F18	lunch	gnegnekini & gneguna	gakourouwana	gendu	24.983	cold and dry
DCT_M_46	7	4.3	F18	dinner	toh & na	gakourouwana	gendu	45.855	cold and dry
DCT_M_47	12	7.4	F06	breakfast	serie	gakourouwana	gendu	32.890	cold and dry
DCT_M_48	12	7.4	F06	breakfast	monie	three-stone fire	gendu	36.908	cold and dry
DCT_M_49	12	7.4	F06	dinner	other	three-stone fire	gendu	28.570	cold and dry
DCT_M_50	20	12.8	F03	breakfast	serie	hand-crafted metal	sow	34.091	cold and dry

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Table N.1. (continued) Daily Cooking Test data for cooking meals.

Test ID	Number of people	Std. adult equiv.[a]	Family ID	Meal time of day	Meal type	Cookstove type	Wood name	Energy use (MJ)	Season
DCT_M_51	20	12.8	F03	lunch	gnegnekini & gneguna	hand-crafted metal	sow	103.746	cold and dry
DCT_M_52	9	6.7	F09	breakfast	serie	three-stone fire	gendu	24.746	cold and dry
DCT_M_53	9	6.7	F09	lunch	gnegnekini & gneguna	low thermal capacity	gendu	52.970	cold and dry
DCT_M_54	9	6.7	F09	dinner	toh & na	three-stone fire	gendu	37.000	cold and dry
DCT_M_55	20	12.8	F03	lunch	gnegnekini & gneguna	hand-crafted metal	barra	102.335	cold and dry
DCT_M_56	5	3.3	F51	breakfast	monie	gakourouwana	gendu	40.795	cold and dry
DCT_M_57	5	3.3	F51	lunch	gnegnekini & gneguna	gakourouwana	gendu	106.257	cold and dry
DCT_M_58	5	3.3	F51	dinner	toh & na	gakourouwana	gendu	36.368	cold and dry
DCT_M_59	5	3.3	F51	breakfast	serie	hand-crafted metal	gendu	44.827	cold and dry
DCT_M_60	5	3.3	F51	lunch	gnegnekini & gneguna	hand-crafted metal	gendu	61.746	cold and dry
DCT_M_61	5	3.3	F51	dinner	toh & na	hand-crafted metal	gendu	49.413	cold and dry

[a]Standard adult equivalence factors defined in terms of sex and age [Baldwin 1987, Joseph 1990]. Children 0-14 years (0.5); adult women 14-59 years (0.8); adult men 14-59 years (1.0); elders 59 years and above (0.8).

Table N.2. Daily Cooking Test data for heating water.

Test ID	Number of people	Std. adult equiv.[a]	Family ID	Time of day	Wood name	Energy use (MJ)	Season
DCT_W_01	3	2.0	F07	evening	gendu	10.520	temperate and rainy
DCT_W_02	5	3.3	F02	evening	gendu	16.754	hot and dry
DCT_W_03	17	10.9	F04	evening	krekrete	36.409	hot and dry
DCT_W_04	21	13.8	F03	evening	gendu	50.716	hot and dry
DCT_W_05	21	13.8	F03	evening	gendu	69.669	hot and dry
DCT_W_06	21	13.8	F03	evening	krekrete	54.877	hot and dry
DCT_W_07	9	6.1	F35	evening	gendu	53.900	hot and dry
DCT_W_08	21	13.8	F03	morning	sow	93.933	cold and dry
DCT_W_09	1	0.8	F01	evening	gendu	7.808	hot and dry
DCT_W_10	12	7.4	F07	evening	gendu	22.894	cold and dry

[a]Standard adult equivalence factors defined in terms of sex and age [Baldwin 1987, Joseph 1990]. Children 0-14 years (0.5); adult women 14-59 years (0.8); adult men 14-59 years (1.0); elders 59 years and above (0.8).

Notes:
- The three-stone fire is used in all tests.
- Water is heated on one stove in all tests.

Table N.3. Daily Cooking Test data for outdoor space heating for primary family fire.[a]

Test ID	Number of people	Family ID	Time of day	Used heating stove?	Wood name	Energy use (MJ)
DCT_H_01	7	F18	morning	no	damba	69.388
DCT_H_02	7	F18	evening	no	damba	104.119
DCT_H_03	7	F18	morning	no	gendu	33.680
DCT_H_04	7	F18	evening	no	gendu	79.772
DCT_H_05	5	F51	evening	no	gendu	54.963
DCT_H_06	6	F07	evening	no	gendu	108.866
DCT_H_07	6	F07	morning	no	gendu	98.035
DCT_H_08	6	F07	evening	no	gendu	63.248
DCT_H_09	3	F52	evening	no	gendu	94.872
DCT_H_10	5	F09	evening	no	sow	149.476
DCT_H_11	7	F03	evening	no	gendu	173.932
DCT_H_12	10	F10	morning	no	gendu	42.534
DCT_H_13	2	F10	evening	no	barra	41.756
DCT_H_14	6	F50	evening	yes	damba	108.581
DCT_H_15	6	F50	morning	yes	damba	74.371
DCT_H_16	8	F15	morning	no	gendu	96.295
DCT_H_17	5	F15	evening	no	damba	32.574

[a]Tests completed between Dec 10 and Dec 20, 2010.

Table N.4. Daily Cooking Test data for indoor space heating for secondary fire used by elderly.[a]

Test ID	Number of people	Family ID	Time of day	Used heating stove?	Wood name	Energy use (MJ)
DCT_H_18	1	F01	overnight	yes	gendu	59.532
DCT_H_19	2	F45	overnight	yes	gendu	67.992
DCT_H_20	1	F01	overnight	yes	barra	51.846

[a]Tests completed between Dec 10 and Dec 20, 2010.

APPENDIX O

DAILY DOMESTIC SOLID FUEL ENERGY USE

Table O.1. Energy use equated to a daily basis for cooking meals.

Number of people	Std. adult equiv.[a]	Family ID	Strata	Meal mass (kg)		Energy use (MJ)	Test IDs
				Total	Dry		
22	13.5	F01	5	41.957	8.278	137.050	OCT_M_02, OCT_M_03, OCT_M_04
20	12.6	F03	4	46.592	9.986	127.621	OCT_M_07, OCT_M_08, OCT_M_09
18	11.9	F04	4	25.860	6.484	126.817	OCT_M_10, OCT_M_11, OCT_M_12
10	6.7	F01	2	19.890	5.740	92.082	OCT_M_14, OCT_M_15, OCT_M_16
20	12.6	F03	4	45.135	11.105	150.362	OCT_M_19, OCT_M_20, OCT_M_21
5	3.3	F02	1	18.705	6.182	87.205	OCT_M_25, OCT_M_26, OCT_M_27
13	8.8	F06	3	22.045	5.885	88.156	OCT_M_32, OCT_M_33, OCT_M_34
7	4.6	F19	2	17.100	4.655	95.708	SCT_M_06, SCT_M_07, SCT_M_08
9.33[b]	6.1[b]	F32	2	16.270	4.720	61.826	SCT_M_09, SCT_M_10, SCT_M_11
17	10.9	F04	4	N/A	N/A	133.424	DCT_M_03, DCT_M_04, DCT_M_05
9	6.1	F35	2	N/A	N/A	107.649	DCT_M_06, DCT_M_07, DCT_M_08
5	3.3	F02	1	N/A	N/A	69.744	DCT_M_09, DCT_M_10, DCT_M_11
22	13.5	F01	5	N/A	N/A	147.563	DCT_M_12, DCT_M_13, DCT_M_14
22	13.5	F01	5	N/A	N/A	173.940	DCT_M_15, DCT_M_16, DCT_M_17
6	4.6	F21	1	N/A	N/A	84.427	DCT_M_18, DCT_M_19, DCT_M_20
6	4.6	F21	1	N/A	N/A	78.396	DCT_M_21, DCT_M_22, DCT_M_23
21	13.6	F03	4	N/A	N/A	238.040	DCT_M_24, DCT_M_25, DCT_M_26
21	13.6	F03	4	N/A	N/A	194.071	DCT_M_27, DCT_M_28, DCT_M_29
20	12.8	F03	4	N/A	N/A	169.853	DCT_M_41, DCT_M_42, DCT_M_43
7	4.3	F18	2	N/A	N/A	82.460	DCT_M_44, DCT_M_45, DCT_M_46
9	6.7	F09	2	N/A	N/A	114.716	DCT_M_52, DCT_M_53, DCT_M_54

[a]Standard adult equivalence factors defined in terms of sex and age [Baldwin 1987, Joseph 1990]. Children 0-14 years (0.5); adult women 14-59 years (0.8); adult men 14-59 years (1.0); elders 59 years and above (0.8).
[b]Average value of three meals with 10 people, 10 people, and 8 people.

Notes: 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).

Table O.2. Energy use on a daily basis for water heating.

Number of people	Std. adult equiv.[a]	Family ID	Water mass (kg)	Energy use (MJ)	Test ID
12	8.4	F03	98.390	62.037	OCT_W_01
12	8.5	F01	62.265	31.498	OCT_W_02
5	3.3	F02	23.260	24.793	OCT_W_03
5	3.3	F09	20.345	23.814	SCT_W_01
7	4.4	F06	60.250	36.872	SCT_W_02
3	1.8	F10	10.680	20.027	SCT_W_03
3	2	F07	N/A	10.520	DCT_W_01
5	3.3	F02	N/A	16.754	DCT_W_02
17	10.9	F04	N/A	36.409	DCT_W_03
21	13.8	F03	N/A	50.716	DCT_W_04
21	13.8	F03	N/A	69.669	DCT_W_05
21	13.8	F03	N/A	54.877	DCT_W_06
9	6.1	F35	N/A	53.900	DCT_W_07
21	13.8	F03	N/A	93.933	DCT_W_08
1	0.8	F01	N/A	7.808	DCT_W_09
12	7.4	F07	N/A	22.894	DCT_W_10

[a]Standard adult equivalence factors defined in terms of sex and age [Baldwin 1987, Joseph 1990]. Children 0-14 years (0.5); adult women 14-59 years (0.8); adult men 14-59 years (1.0); elders 59 years and above (0.8).

Notes: Families heat water for bathing once per day, no modification needed to equate to a daily basis.

Table O.3. Energy use on a daily basis for roasting peanuts.

Number of people	Std. adult equiv.[a]	Family ID	No. cooks	Peanut roasting		Energy use one cook (MJ)			Energy use all cooks (MJ)			Test ID
				Mass one roast (kg)	Roast rate (times/wk)	One roast	Per week	Per day	One roast	Per week	Per day	
17	10.7	F12	1	1.600	3.00	11.453	34.359	4.908	11.453	34.359	4.908	OCT_P_01
12	8.4	F50	2	11.700	0.25	58.375	14.594	2.085	58.375	29.187	4.170	OCT_P_02
23	14.5	F10	3	3.160	1.00	23.303	23.303	3.329	23.303	69.909	9.987	OCT_P_03
7	4.3	F56	1	1.420	1.00	16.695	16.695	2.385	16.695	16.695	2.385	OCT_P_04
7	4.9	F09	2	0.865	1.00	6.904	6.904	0.986	6.904	13.807	1.972	SCT_P_01
13	9	F16	3	1.880	0.50	29.625	14.812	2.116	29.625	44.437	6.348	SCT_P_02

[a]Standard adult equivalence factors defined in terms of sex and age [Baldwin 1987, Joseph 1990]. Children 0-14 years (0.5); adult women 14-59 years (0.8); adult men 14-59 years (1.0); elders 59 years and above (0.8).

Notes: Peanuts are roasted by all women who cook in the family, and retained for personal use in meals when it is their turn to cook. Energy used to roast peanuts for the entire family must include the energy use from all cooks in the family.

Table O.4. Medicine use rate for the village by season.

Period of medicine use	Average times per day for entire village	Purpose
all year	4.53	magic protection/sickness, wash newborn baby daily
additional use during temperate and rainy season & cold and dry season	5.74	malaria prevention, malaria treatment, eye ache, head ache, cold, flu

Table O.5. Aggregate daily rate of steeping tea for the village for each season.

Season	Number of families by steeps of tea per day[a]					Total steeps in village
	Zero	One	Two	Three	Four	
hot and dry	3	7	23	24	3	137
temperate and rainy	8	45	7	0	0	59
cold and dry	8	44	8	0	0	60

[a]Mean and standard deviation provided for energy use, medicine use varies by family demographics and by season.

Table O.6. Aggregate daily energy use for outdoor space heating for primary family fire.

Family ID	Energy use (MJ)	Test IDs[a]
F18	173.507	DCT_H_01, DCT_H_02
F18	113.451	DCT_H_03, DCT_H_04
F51	54.963	DCT_H_05
F07	108.866	DCT_H_06
F07	161.283	DCT_H_07, DCT_H_08
F52	94.872	DCT_H_09
F09	149.476	DCT_H_10
F03	173.932	DCT_H_11
F10	84.291	DCT_H_12, DCT_H_13
F50	182.952	DCT_H_14, DCT_H_15
F15	128.870	DCT_H_16, DCT_H_17

[a]Two test IDs indicate daily energy use expressed by the sum of two tests (morning and evening) observed in a 24-hour period.

Table O.7. Aggregate daily energy use for indoor space heating for secondary fire for elderly.

Family ID	Energy use (MJ)	Test ID
F01	59.532	DCT_H_18
F45	67.992	DCT_H_19
F01	51.846	DCT_H_20