2015

Development and use of an integrated systems model to design technology strategies for energy services in rural developing communities

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Development and use of an integrated systems model to design technology strategies for energy services in rural developing communities

by

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A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Mechanical Engineering

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Iowa State University

Ames, Iowa

2015

"*A razor may be sharper than an axe but it cannot cut wood*"

−African Proverb

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

AC	annual cost
AED	annual energy delivered
AEE	annual embodied energy
AEI	annual energy of implementation
AEU	annual energy use
AH	annual hours
AHR	annual forest harvest rate
AQG	air quality guideline
C	cost
cap	capita
EAC	equivalent annual cost
EE	embodied energy
EF	emission factor, energy basis
ef	emission factor, mass basis
f	fraction
GWC	global warming commitment
GWP	global warming potential
i	iteration counter
L	lighting output
LHV	lower heating value
m	mass

N	quantity
Q	firepower
Quality	quality of life metric
r	discount rate
RHI	relative hazard index
VH	valued hours (lighting)
w	weight
x	variable
y	output
β	fuel price elasticity
η	efficiency

subscripts

as-rec'd	as-received
base	baseline
cap	capacity
capital	capital
coll	collected fuel
cook	cooking
dis	displacement
elec	electricity
energy	human caloric energy
fuel	fuel type

HH	households in the village
heating	space heating
i	use index
imp	implementer
j	device index
k	emission species index
l	material index
labor	human labor
light	lighting
LCA	life cycle analysis
m	quality of life index
maint	maintenance
mech	mechanical
NRB	nonrenewable
operating	operating
post	after intervention
pre	before intervention
prep	fuel preparation
reb	rebound
shadow	shadow value of time
subsidy	subsidy
time	fuel collection time
TSF	three-stone fire

useful	useful lifetime
unv	unvented

ACKNOWLEDGMENTS

I am extremely grateful for the opportunity to have learned and applied engineering tools and analyses in the context of this enjoyable and purposeful research. None of my present or previous educational experiences would have been possible if not for my long-time advisor and role model, Professor Mark Bryden. His wise guidance coupled with an understanding of my values and faith in my abilities have continually encouraged me to take risks and pushed my personal and professional development. His ideas, foresight, and mentoring have kindly shaped my life and career over the last 15 years in non-traditional ways that I had never thought possible and provided me with opportunities for engaging and meaningful work, lifelong learning, and ultimately the chance to offer the same to others. Although the bar is set improbably high, I will strive to contribute the same level of wisdom and generosity to my students and colleagues in the future.

I would also like to offer my sincere thanks to Iowa State University and all of the faculty, staff, and students that have made my tenure such a pleasure. I am particularly grateful to Professor Kris Bryden for her meticulous editing and cultivation of my writing and presentation skills, and to my committee members, Professors Richard LeSar, Arne Hallam, Xinwei Wang, and Mark Mba-Wright for their guidance and encouragement throughout the course of this and previous research. I would also like to thank my colleague Professor Nathan Johnson and other researchers at Iowa State for the comprehensive data and analysis of the Malian village without which this work would not have been possible.

I would like to extend my gratitude to the National Science Foundation Graduate Research Fellowship Program and the US Department of Energy Ames Laboratory which provided the funding to allow me to pursue this line of research. And I would also like to thank my long-time friends and colleagues of Aprovecho Research Center, including Dean Still, Damon Ogle, Sandra Moen, Professor Tami Bond, Dr. Dale Andreatta, Dr. Larry Winiarski, the late Ken Goyer, and the global cookstove community for the inspiration, opportunities, and background that developed my experiences and interest in this area over the course of many years and many collaborations. I also owe much appreciation to my mother-in-law, Loree Rose, who was quick to jump in at any time my work took me away from my family to provide joyful, loving, and thoughtful caregiving for my young son and encouragement for me.

I would not be the person I am today without my wonderful parents, Sharon and the late Warren Hudelson, who raised me to appreciate the value of energy and conservation while living in an isolated rural Minnesotan homestead fueled by biomass for a good portion of my childhood. As a daughter of the public affairs spokesman for the local electric power company, I grew to appreciate the level of importance of energy in communities as I listened to my father on the radio or TV news explaining how long the electricity would be out after a Midwest storm took down the power lines. And because to this day my mother still cooks on a wood cookstove for 9 months out of the year, I can appreciate the value that a lifetime of expertise, multitude of functions, and cultural integrity that traditional energy services have to offer. I am grateful every day for their love and their fortitude, and for the opportunities for education and life experience that they provided.

I would also like to honor my husband Lance for his artful advice on my challenges and his constant support of my purpose and path since the beginning of my journey in energy for developing countries and our journey together over 15 years ago. His grounding and free-spirited presence has given me the courage and freedom to explore the world and my interests and ultimately create a fulfilling career that allows me to pursue my passions, all from the foundation and sanctuary of a loving family. His perspective never ceases to surprise, inspire, and guide me.

Finally, I am forever thankful to my son Odin whose existence incited this accomplishment in higher education and whose upcoming education will surely lead to many adventures in the future. May this work help to make the world a healthier and happier place for his generation and beyond.

ABSTRACT

For the 40% of the world’s families living in energy poverty today, energy services are provided almost exclusively by the same three-stone fires that have been used for millennia. The pollution from the pervasive use of these fires represents the second leading cause of death for women worldwide and contributes significantly to local and global climate change. Improving access to clean energy services can facilitate improved health and livelihoods and serve as a precursor to other economic and social development. Yet within these diverse, complex, and highly-localized communities, the most effective strategies to provide clean energy are not clear; and success of programs to provide technologies such as biomass cookstoves or subsidize fuels such as LPG or electricity has often been limited. This is because an energy carrier or conversion technology is only a small component of a much larger energy system that includes a complex set of needs, constraints, and other variables at the household, community, and global scales. Within this system exists a range of technical, economic, social, and environmental objectives that often conflict between these scales to create an imbalance between stakeholders; and outcomes vary widely based on technology design choices and local conditions. As a result, development of effective solutions requires a clear understanding of the direct and indirect impacts of design decisions that are rooted in the fundamental interactions between energy, the environment, and people.

In order to assist in understanding these interactions in a systematic fashion, this dissertation develops a probabilistic unified modeling approach that seeks to facilitate energy system design by predicting outcomes in terms of a set of multi-disciplinary considerations and objectives. This approach incorporates a large parameter space including local energy needs,

demographics, fuels, and devices to create a comprehensive analysis of potential strategies in terms of a range of technical, environmental, economic, and social outcomes. While recognizing that there is no single 'best' solution, this methodology allows the designer to investigate and understand trade-offs between conflicting and competing objectives, the effects of usability and multi-functionality, sensitivities of input parameters for identification of prominent and critical factors, the impacts of uncertainty in decision-making, and the potential for compromise and integrated strategies that provide sustainable and effective energy services.

The model is used to explore a number of scenarios to provide energy services in a remote off-grid village in Mali for which detailed measures of disaggregated energy use are available. In addition to detailed analysis of the baseline situation, strategies investigated include the introduction of (1) general improved biomass cookstoves, (2) advanced biomass cookstoves, (3) communal biomass cookstoves, (4) LPG cookstoves, (5) solar water heaters, and (6) community-charged solar household lighting. Following this and other analyses, an integrated strategy for energy services is developed.

The results show that the factors with the largest impact on the outcome of a technology strategy include the rate of user adoption, value of time, and biomass harvest renewability; in contrast, parameters such as cookstove emission factors may have less impact on the outcome. This suggests that the focus of village energy research and development should shift to the design of technologies that have high expected user adoption rates. That is, the results of this study support the hypothesis that the most effective village energy strategy is one that reinforces the natural user-driven process to stack technologies while moving toward efficient and convenient energy services. A comprehensive strategy that provides the current state-of-the art technologies to optimally meet each specific energy need in the Malian village with a population of 770—including advanced cookstoves, LPG cookstoves, solar water heaters, and solar battery lighting systems—is expected to annually create 2.5 TJ of energy savings, 500 metric tons of CO_{2e} savings, a 40% reduction in health risk, and offer substantial improvement of quality of life. Moreover, this strategy will reduce operating costs to the users including time by an estimated $1,000 (US) each year. Such a strategy is expected to cost $12-$13 per person per year to purchase and maintain the necessary technologies if supplied by outside financing, a figure which might double or triple when implementation costs are included. This is a relatively small expense in comparison to the projected cost of $110 per person per year to provide the necessary agricultural, health, and educational inputs needed for the Millennium Villages, a figure reported to be well within the range committed by international aid organizations.

CHAPTER 1

INTRODUCTION

The design and dissemination of affordable, clean, and sustainable energy services for the 40% of the world's population currently living in energy poverty continues to be one of the most challenging problems of the 21st century. Today nearly 2.7 billion people do not have access to clean cooking facilities, and 1.4 billion people lack a bare minimum of electric lighting (IEA, 2010; DFID, 2002). In many of these often rural communities, approximately 95% of energy needs are met by combustion of biomass in traditional three-stone fires (TSF), which causes harm to health, climate, and livelihoods (Johnson and Bryden, 2012a; Bhandari and Stadler, 2011; Lim et al., 2012; Bond et al., 2013). Off-grid users pay nearly 20% of global lighting expenses yet receive less than 0.1% of global lighting services, and these lighting services are provided by polluting devices, such as kerosene lanterns and disposable batteries (Mills and Jacobson, 2011). The effects of this insufficient, expensive, and harmful energy supply creates a poverty trap in which subsistence-level families are not able to secure sufficient energy to meet their needs for basic survival, let alone provide energy for any income-generating or educational uses that might help them to rise out of poverty. Because access to energy is inextricably linked with economic, educational, and social development, energy solutions that help to effectively meet people's basic and productive energy needs can directly lead to addressing other pressing issues such as the millennium development goals for poverty alleviation, health and environmental protection, and gender equality (Modi et al., 2006).

Access to satisfactory energy services is fundamental to fulfilling the most pressing goals of the 21st century, including meeting the needs for basic survival for all, driving economic growth, and facilitating human development (Gaye, 2007). Increases in income, education, and health are only possible with access to ample energy, a relationship that is clear when one compares the development indices in Africa to that of North America where the total primary energy consumption per capita is sixteen times higher (IEA, 2014). Not only do those living in energy poverty miss out on the services associated with adequate energy supplies, but they are also burdened with the negative impacts at local, national, and global levels due to the traditional combustion of solid fuels that threatens health and disrupts the ecological balance. Although lesser developed countries have done little to contribute to the sources of anthropogenic climate change, they are more susceptible to the effects of it because they so heavily rely on the local environment and can less afford the cost to adapt to changes in climate (Gaye, 2007). In essence, "poor families spend one-fifth or more of their income on wood and charcoal, devote one-quarter of household labor collecting fuelwood, and then suffer the life-endangering pollution that results from inefficient combustion" (Sovacool, 2012). In his remarks at Rio+20 calling for an end to energy poverty, UN Secretary General Ban Ki-moon recalled growing up in Korea studying by the light of a dim smoky oil lamp. Candles were reserved for preparing for exams because they were "too expensive to use for ordinary homework" (Ki-moon, 2012). Clearly the social, economic, political, and moral concerns associated with this hardship and insecurity make systematic efforts to reduce this inequality a critical issue of our time.

Although the motivation to address energy needs in developing countries is clear, the optimal strategies to do so are not. Electrification has reportedly reached nearly 80% of the global population, yet electricity is often unaffordable and unreliable and is not used to meet the needs for thermal energy such as cooking, space heating, and warming water, which can represent over 96% of energy needs in a typical village (Johnson and Bryden, 2012a; Madubansi and Shackleton, 2006). These energy needs represent varying degrees of intensity, cultural preferences, and fuel resources in communities across the globe that are diverse, remote, and based on informal economies with income levels less than $2 per day, thus constraining the solutions space differently in different areas. There are many strategies for meeting energy needs ranging from micro-grid hybrid electrification, improved or advanced biomass cookstoves, cleaner fuels, changes in practice, solar lighting systems, and others. Choosing between these options is complex, and a strategy that holistically considers the energy ecosystem of the community is needed rather than a one-size-fits-all technology. The primary goal of this research is to evaluate the energy needs, potential technological components, and impact of strategies within the energy system of a rural village, and to understand any trade-offs between the multiple objectives that result in stakeholder imbalance.

The development of improved energy services seeks to meet a wide range of technical, economic, environmental, health, and social objectives. These encompass many outcomes from preserving local forests and the climate to lowering capital and opportunity costs and increasing convenience and safety for the user, among others. Although all of these are important, there are often competing and conflicting objectives between stakeholders ranging from the global organizations to the individual user viewpoint. For example, a low-emissions cookstove may emit fewer greenhouse gas emissions than the three-stone fire but may be too expensive and inconvenient for the user and thus will not be used. Or a solar lighting system may improve quality of life and provide educational benefits to the family but may offer relatively little savings to forests and health, and it may have a high initial cost and require ongoing maintenance. In both cases, the strategy is likely to fail because it is either not adopted by the user or not pursued by the implementer.

A further challenge lies in predicting the relative savings offered by one device over another given the levels of adoption and sustained use in the community setting. Impacts at the village scale directly depend on the fraction of users in the village that will adopt the devices and the uses for which they will choose to use it. For example, a proposed cookstove may be used only to provide cooking services, or it may be able to be used for specialty cooking and water heating as well. In addition, natural consumer behaviors, such as rebound (increased use due to increased efficiency) and device stacking (the use of multiple fuels and technologies) will occur. When these questions are accounted for, the analysis is not nearly as straightforward as predicting fuel savings based on comparing the efficiency of a proposed cookstove with that of the three-stone fire. Outcomes in the field become even more difficult to predict when the confounding effects of in-use performance and the multi-functionality of the three-stone fire are included as well. In addition, financial factors such as purchase, fuel, and maintenance costs are subject to the consumer discount rate, which reflects the high time value of money for the user due to a lack of cash reserves and therefore a high annualized investment cost. Social factors such as convenience, safety, and consumer preference dictate the levels of affordability and consumer acceptance as well (Figure 1.1). Attention to all these factors is necessary to understand the expected overall performance of these small energy systems and ultimately to develop tailored, locally embraced, and lasting energy system solutions.

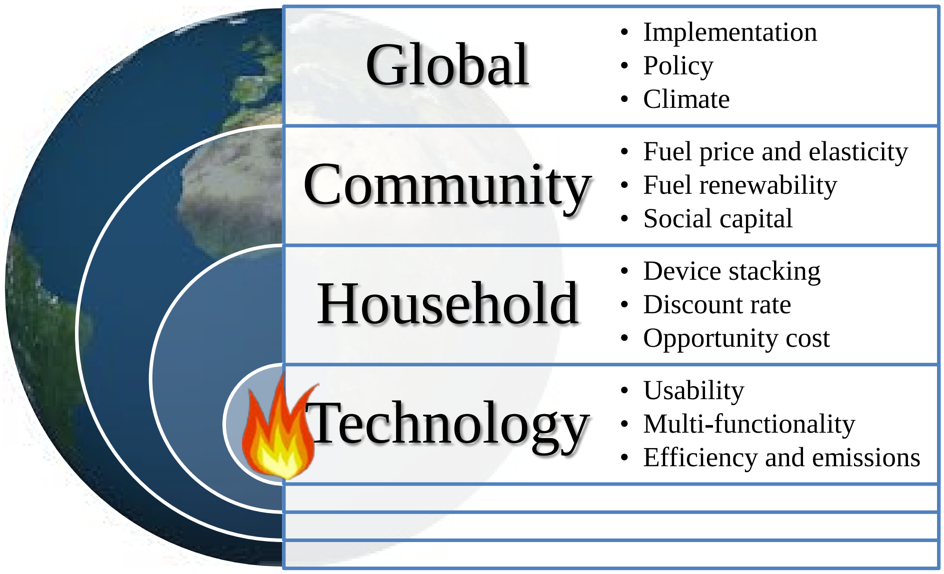

Figure 1.1 Factors in the village energy system

There are strategies that can adequately address the goals of all stakeholders. The challenge presently lies not predominantly in the engineering of cookstoves, water heaters, or solar panels, but in their selection and implementation within the overall energy system of a given community. Optimal strategies are created not by designing a highly efficient device in isolation and then seeking a consumer base or by simply asking the consumer to define their solution, but instead by selecting and tailoring a technology within the context of the greater community energy system.

Based on this system-level viewpoint, an analysis framework and integrated model is needed to assist the design process for technology strategies that are both efficient and effective. In the framework developed for this research, shown in Figure 1.2, the designer or implementer investigates the outcomes produced by potential technologies subject to local constraints through use of a comprehensive model. These constraints include the local energy needs, available fuels, and demographic variables that influence the application of the technology. The model includes quantitative consideration of the systems-level performance and adoption factors in the community, which dictate how and how much the technology will be used in order to predict the impacts it will have in comparison to the current scenario. Based on reported outcomes of these options in the context of the technical, environmental, economic, and social objectives of the program and community, the designer can then make informed decisions regarding the most appropriate choice of technology, policy, and implementation strategies.

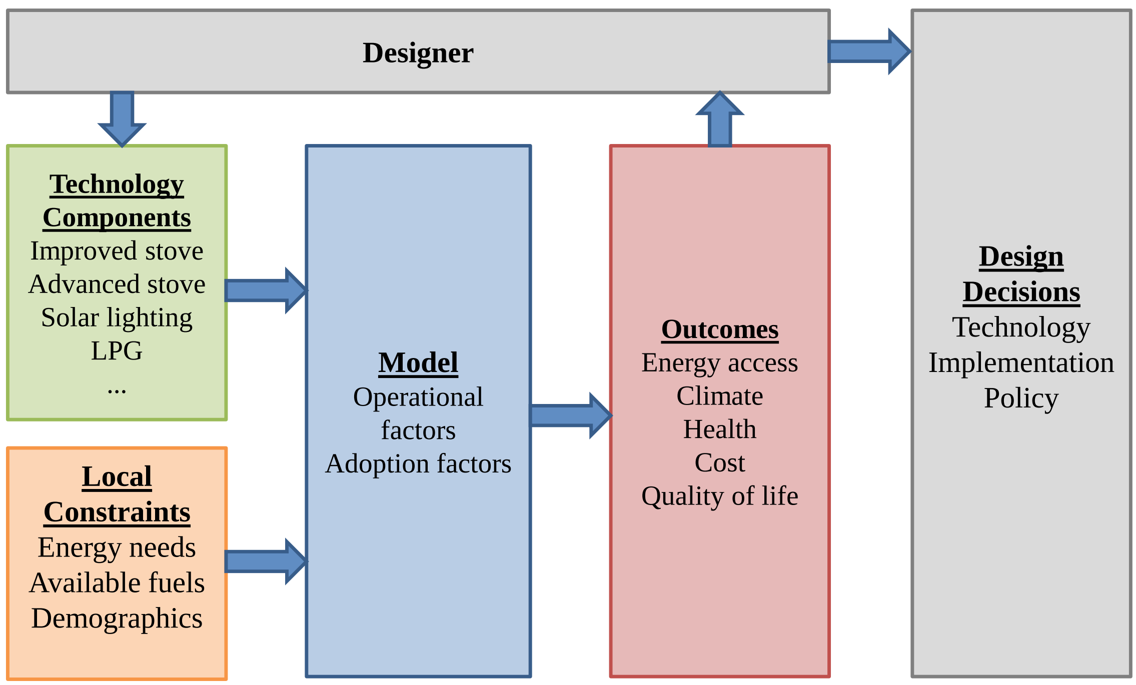

Figure 1.2 Energy system design framework

Despite this need for a holistic approach to rural energy development in order to aid in the alleviation of energy poverty, there are no existing comprehensive models that adequately address these specific needs and particular conditions in the millions of households in lesser developed countries. Energy planning software packages do not currently incorporate the nuances of the off-grid needs for non-commercial energy in informal economies. There are few models that incorporate both quantitative and qualitative aspects from economic, social, and engineering theory into a model of the village system as a whole using disaggregated inputs of energy use and performance. Although there are a number of models for village electrification, there are fewer models that specifically consider thermal energy needs such as cooking, space heating, and warming water. There are a number of models that address single aspects of various technical, economic, and environmental objectives for village energy. Of these, econometric factors relating to not only the technology but also the user and community, such as fuel/device stacking and rebound, are not adequately incorporated. Moreover, there are not any models that address a technology as a component within the larger community energy system and integrate the range of objectives described above.

To address this need, this dissertation develops an integrated multi-objective model that is used to examine community-scale outcomes on an annual basis. Components from a menu of potential changes in practice, fuels, and devices are applied to address the thermal, luminous, mechanical, and electrical energy needs in a rural developing community. Using empirical disaggregated energy use data, this model predicts the net improvement (or decline) created by the introduction of a new technological component relative to current conditions for a number of outcomes in terms of five categories of objectives. These technical, environmental, economic, and social outcomes include (1) primary energy consumption and useful energy delivered, (2) climate impacts, (3) health impacts, (4) costs over time (both financial and opportunity) to user and donor, and (5) user acceptance as indicated by a number of social metrics designed to indicate a relative improvement in quality of life for the user. While recognizing that there is no single ‘best’ solution, it is hoped that a tailored systems-level approach such as this will help energy service implementers to explore the large parameter space and to understand the relative impacts, trade-offs, sensitivities, and critical parameters that dictate system-level outcomes needed to develop effective strategies to meet community energy needs.

Following development of the model, the effects of the application of a variety of technologies for a number of energy services at the community scale on an annual basis are examined. Several common single-technology strategies are compared, including (1) general improved biomass cookstoves, (2) advanced biomass cookstoves, (3) communal biomass cookstoves, (4) LPG cookstoves, (5) solar water heaters, and (6) community-charged solar household lighting. An integrated strategy that assigns the most effective technology to each energy need is also developed and compared. Following that, the effects of changes to the technology design characteristics and operational and adoption factors are investigated as well. In each case the goal is to identify the design choices and parameters that will help to generate the largest impacts in terms of not only energy use and cost, but also environment, health, and social concerns.

This dissertation includes the necessary background, methodology, and analysis to address these issues. Chapter 2 reviews the options for technological components and factors impacting the outcome of technologies on the village energy system, and it describes the objectives of improved village energy services. Chapter 3 reviews previous modeling efforts relevant to village energy. Chapter 4 presents the theory and development of the systems model, including the databases of energy needs, technologies, fuels, and local variables, as well as the sub-models used to predict the multiple areas of outcomes. Chapter 5 uses the model to investigate and compare major categories of energy technologies and develops an integrated strategy. Chapter 6 investigates the impact of application factors such as energy needs, fuel supply, and variability on the outcomes. Chapter 7 considers the impact of design choices such as usability, multi-functionality, efficiency, emissions, cost, and durability on outcomes of technologies within the system. In Chapter 8, the factors influencing adoption within a community are investigated. Finally, Chapter 9 summarizes key findings, draws conclusions, and suggests future work.

CHAPTER 2

BACKGROUND

The success of a village energy program is tightly tied to conditions within the village energy system. In this chapter the energy services needed, the components that can provide those services, the factors dictating their performance and use, and the objectives of providing clean energy services are explored.

The demand for energy is a “derived demand,” as it is not the energy itself that is needed but the services (such as lighting, cooking, heating) that it provides (DFID, 2002). The use of energy by humans is fundamentally categorized into three levels of hierarchical needs: survival, productivity, and comfort. At the base is energy used to meet needs for basic survival, which includes cooking, warming water, space heating, essential lighting, and communication. Once these basic survival needs are met, energy can then be used for productive or income-generating tasks, including mechanical energy for food processing, agriculture, manufacturing, mass transport, and lighting for education and income generation. Finally, the use of energy for modern comfort and convenience such as air conditioning, automated appliances, and private transportation is possible once excess income and time are available due to gains in productivity (Sovacool, 2012). It is the transition from striving to secure the minimum energy needed for basic survival to applying it for income-generation or education that begins to break the cycle of energy poverty.

In a typical rural developing community where a mix of thermal, luminous, mechanical, and electrical energy are used within the residential, commercial, public, transport, and agriculture sectors, the majority of energy is consumed to meet basic survival needs.

Measurements of energy consumption in a village and correlated factors have been characterized by a number of researchers. Table 2.1 catalogues many studies but is not exhaustive. In particular, Johnson and Bryden (2012a) performed a study of energy consumption and use for a village in Mali that catalogues the disaggregation of energy consumption in that village, shown in Figure 2.1. In this dissertation the term “the Malian village” refers to the village in Johnson and Bryden’s study. These data showed that energy used to meet basic needs represents 92% of the energy use in the village (Figure 2.1B). These basic needs are met in the residential sector, which consumes the most significant fraction, or 92%, of total energy (Figure 2.1C), a level similar to that in many rural developing communities (Bhandari and Stadler, 2011). Moreover, approximately 94% of the energy services in this community are provided by the traditional three-stone fire.

Most, or 96% in that study, of the energy used in a rural community is required in the form of thermal energy, or heat (Figure 2.1D). This heat is delivered in a variety of forms. It is primarily used for cooking, which includes typical boiling and frying processes, as well as specialized cooking procedures, such as roasting nuts and rendering oil, making medicine, preparing feed for livestock, steeping tea, seasonal traditions, and baking bread. The second major thermal energy use is heating water for bathing and washing. Of nearly an equal magnitude to that of water heating, space heating is needed indoors on a seasonal and regional basis in many communities, often at night when fire tending is minimal. Lighting in the household is important after sunset as are portable lights for use outside the home. Disposable batteries for flashlights and other small devices provide a negligible amount of energy, yet can often represent the most significant energy expenditure in households (Johnson and Bryden, 2012a).

Table 2.1 Summary of rural household energy measurement publications

			Measurements							Factors												
										Region			Household			Fuel						
Country	No. Village/Region	No. HH	Sector Fraction	Fuel Fraction	HH Use Fraction	Task Fraction	Trends/Projections	Energy Expenditure	Consumption Rates	Rural/Urban	Climate	Seasonal	Income/Wealth	HH Size	Age, Education, Gender	Price	Availability	Technology	Electrification	Year(s)	Regression	Reference
Global																						
8 countries													x	x	x	x			x	93-00	x	Heltberg, 2004
Africa																						
Sub-Saharan				x															x			Prasad, 2011
Sub-Saharan													x			x				70-90	x	Cuthbert, 1998
Sub-Saharan				x				x					x			x				1987		Baranzini, 1996
Sub-Saharan	10	3000		x	x			x	?		x					x	x			2011		Adkins, 2012
West Africa			x	x					x	x										88-93		Brocard, 1998
Cameroon	31	222	x	x					x	x		x				x						Forkong, 2002
Chad/Cameroon								x		x			x		x	x	x			2013		Vitali, 2014
Eritrea	11	2065	x	x					x	x												Arayal, 1999
Eritrea			x	x					x											1998		Habtetsion, 2002
Ghana	3	371		x					x													Osei, 1993
Kenya	13	2202	x	x				x	x	x			x	x	x	x	x	x		1997		Kituyi, 2001
Malawi	4	200							x			x					x			1990		Brouwer, 1997
Mali	1	60			x	x			x			x		x				x		2012	x	Johnson, 2012b
Mali	1	60	x	x	x	x			x			x		x			x			2012		Johnson, 2012a
Mozambique		4747		x				x	x	x			x		x				x	2002	x	Arthur, 2010
Mozambique		8147		x				x	x	x			x		x	x			x	2002	x	Arthur, 2012
Nigeria			x	x					x	x			x	x	x		x	x		1995		Kersten, 1998
South Africa		8500		x				x		x			x						x	1993/4		Davis, 1998

Table 2.1 Continued

Uganda				x					x	x							x			2003		Winrock, 2007
Uganda													x	x		x	x				x	Egeru, 2010
Uganda		220								x			x	x	x			x		2008	x	Walekhwa, 2009
Zambia				x																2000		Haanyika, 2008
Zimbabwe				x					x	x			x	x		x	x			1984	x	Hosier, 1987
Zimbabwe	5	529		x					x	x				x			x	x		1995		Marufu, 1997
Zimbabwe	13	2520		x		x			x	x	x	x		x			x			1997	x	Marufu, 1999
Asia																						
Multiple				x					x	x			x	x		x				77-82		Leach, 1987
India & China				x			x		x	x			x		x					various		Pachauri, 2008
Bangladesh				x					x				x		x	x				2004	x	Barnes, 2011
Bangladesh	1	61	x	x					x				x	x							x	Biswas, 1997
Bangladesh	1	120		x				x	x				x		x		x					Miah, 2010
Bangladesh		180		x				x	x	x			x		x		x			2008		Miah, 2011
Bangladesh	1	45		x									x				x			2001		Miah, 2003
Bangladesh	1	60		x				x	x	x			x	x	x		x	x		2003		Miah, 2009
Bhutan				x	x					x			x	x	x	x			x	2007	x	Rahut, 2014
China	6	3240		x	x				x				x									Wang, 1996
China	20	401		x				x			x		x	x	x	x	x			2004	x	Peng, 2010
China	9	~4000		x									x	x	x	x				89-06	x	Yan, 2010
China		1050											x	x	x					03-05	x	Yu, 2011
Cambodia		767		x	x				x				x	x	x			x				San, 2012
India				x					x	x			x							2000		Ailawaldi, 2006
India				x			x		x				x							2005		Balachandra, 2011
India				x			x			x			x					x		2003		Bansal, 2013
India				x						x			x						x	2001		Bhattacharya, 2006
India				x			x	x	x	x			x							83-00		Viswanathan, 2005
India			x	x	x	x			x											2004		Devi, 2009
India				x					x	x			x							2000	x	Ekholm, 2010
India				x				x					x	x	x	x				1999	x	Gundimeda, 2008
India		118000		x						x			x	x	x					2000	x	Rao, 2007
India		500		x				x					x	x	x	x				2005	x	Gupta, 2006
India	4	180		x												x	x			1997	x	Heltberg, 2000
India	1	250		x	x								x	x				x		2007		Joon, 2009
India	6				x				x		x	x		x	x	x	x			2008		Kumar, 2009

Table 2.1 Continued

India									x	x			x	x	x					1993	x	Pachauri, 2004
India				x			x	x	x	x			x	x	x					83-00	x	Pachauri, 2004
India	29	1304		x	x	x	x		x		x	x	x	x	x					various		Ramachandra, 2000
India		1000		x									x								x	Reddy, 1995
India		1000		x									x								x	Reddy, 1996
India				x			x			x			x					x		2000		Reddy, 2003
India				x			x			x			x					x		various		Reddy, 2009
India	6	560	x	x	x				x				x	x			x			1977	x	Astra, 1981
India							x			x			x	x	x	x				various		Reddy, 2009
India	6	508		x	x				x	x	x	x										Sarmah, 2002
India	4	200					x						x	x	x	x			x	various	x	Sehjpal, 2014
India	10	200							x		x	x								2007		Singh, 2010
India	638	39000		x					x	x	x					x				85-89	x	Sinha, 1997
India							x						x	x	x					83-00	x	Kavi Kumar, 2007
India							x	x					x	x	x	x	x		x	70-00	x	Kemmler, 2007
India	80												x		x				x	2009	x	Oda, 2011
Indonesia		4793								x			x		x				x	97-07	x	Lamarre-Vincent, 2011
Laos	1	30		x			x	x	x										x	2007		Mustonen, 2010
Nepal			x	x			x													1995,05		Bhandari, 2011
Nepal		2035											x	x	x		x		x	2001	x	Macht, 2007
Nepal		52											x	x	x		x			2002	x	Sapkota, 2008
Nepal													x			x	x				x	Amacher, 1996
Pakistan													x	x						2003	x	Chaudhuri, 2003
Korea	1		x	x				x												2000		Von Hippel, 2008
Sri Lanka		160		x	x								x						x			Wijayatunga, 2003
Thailand	3	288		x					x	x			x	x						2007		Nansaior, 2011
Central & South America																						
Guatemala				x				x		x			x	x	x	x				2000	x	Heltberg, 2005
Guatemala		7276		x					x	x			x	x	x	x		x		2000	x	Edwards, 2005
Mexico			x	x	x		x		x	x			x			x			x	84-06		Rosas-Flores, 2010

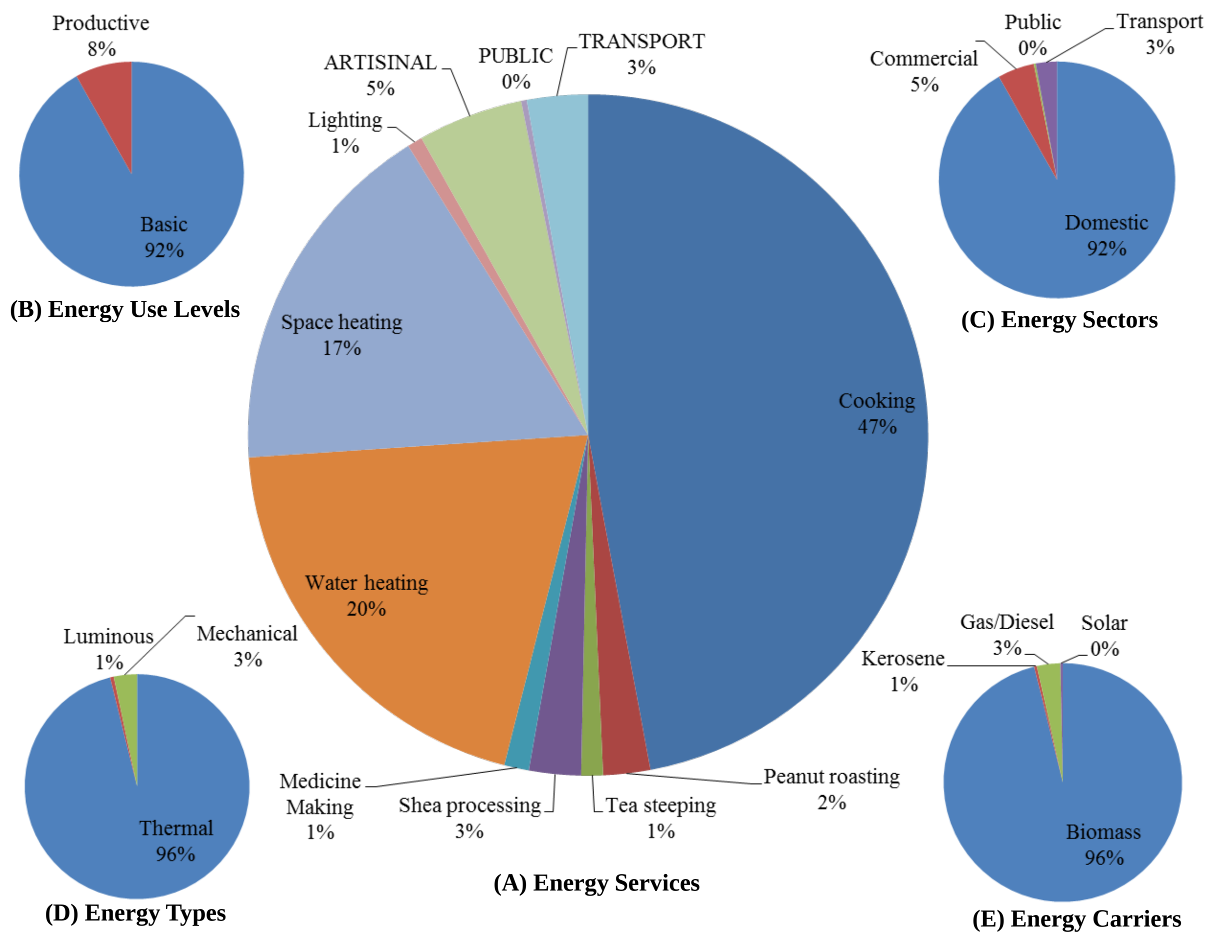

Figure 2.1 Energy services (A), use level (B), sectors (C), types (D), and carriers (E) in a rural village (data from Johnson and Bryden, 2012a)

Beyond the residential sector, the commercial sector in a rural developing community typically includes artisanal activities (such as bakeries, restaurant and tea shops, pottery and brick manufacturers, woodsmiths and blacksmiths) and services, such as grain milling and repair. The public sector includes hospitals, schools, and government locations (Johnson and Bryden, 2012a; Arayal, 1999). Energy services that benefit the public include pumping drinking water up from clean aquifers, lighting schools, or equipping medical centers with electricity to provide lighting, refrigeration for vaccines, and to operate life-saving medical equipment. Despite the clear need for electricity in medical centers, in Sub-Saharan Africa it was recently estimated that

26% of the 4,640 medical clinics have no electricity, and babies are delivered in candle light (Adair-Rohani et al., 2013).

The obstacles to providing these energy services while reducing the lack of quality, quantity, and convenience are numerous. Although electrification of rural villages through grid extension, micro grids, or home systems powered by fossil and/or renewable fuels is an important and ongoing goal, electricity has been shown to not adequately supply all rural energy needs. The basic electric consumption for newly electrified rural communities is estimated at 25 W/cap, in comparison to an average of 1,800 W/cap in the US and 300 W/cap globally (Fulkerson, 2005). For reference, a medium electric stove burner draws approximately 1,500 W. Therefore, even in areas that are connected to the grid, the inadequate amperage, cost, and unreliability of electricity makes the electricity supply unsuited for thermal tasks. Recent estimates indicate there are 1.4 billion people without electricity, yet 2.7 billion people cook and heat with biomass (IEA, 2010), suggesting a minimum of 1.3 billion people have access to electricity but do not use it for thermal energy. Because such a high fraction of village energy needs are thermal, studies by Madubansi and Shackleton (2006) and others have found no significant decrease in fuelwood consumption after village electrification although the benefits of electricity are significant and include greater access to energy services at lower prices (Barnes, Khandker and Samad, 2011). Because affordable commercial energy such as electricity and gas are simply not available in rural communities due to income and infrastructure constraints, a combination of technologies utilizing locally available energy supplies are needed.

2.1 Technological Components in the Village Energy System

Despite this general lack of access to affordable commercial fuels in rural communities, there are a number of technological components that help to effectively utilize local energy supplies to meet energy needs. Examples and categorization of these are shown in Figure 2.2. Technological components include an array of devices, such as different types of biomass cookstoves, lighting systems, water pumps, and more. Fuel components include the available biomass, processed biofuels, and fossil fuels. And because technology by definition can include any application of knowledge, these components can also come as an informed change in practice, such as using embers to ignite fires more quickly or cooking with added ventilation.

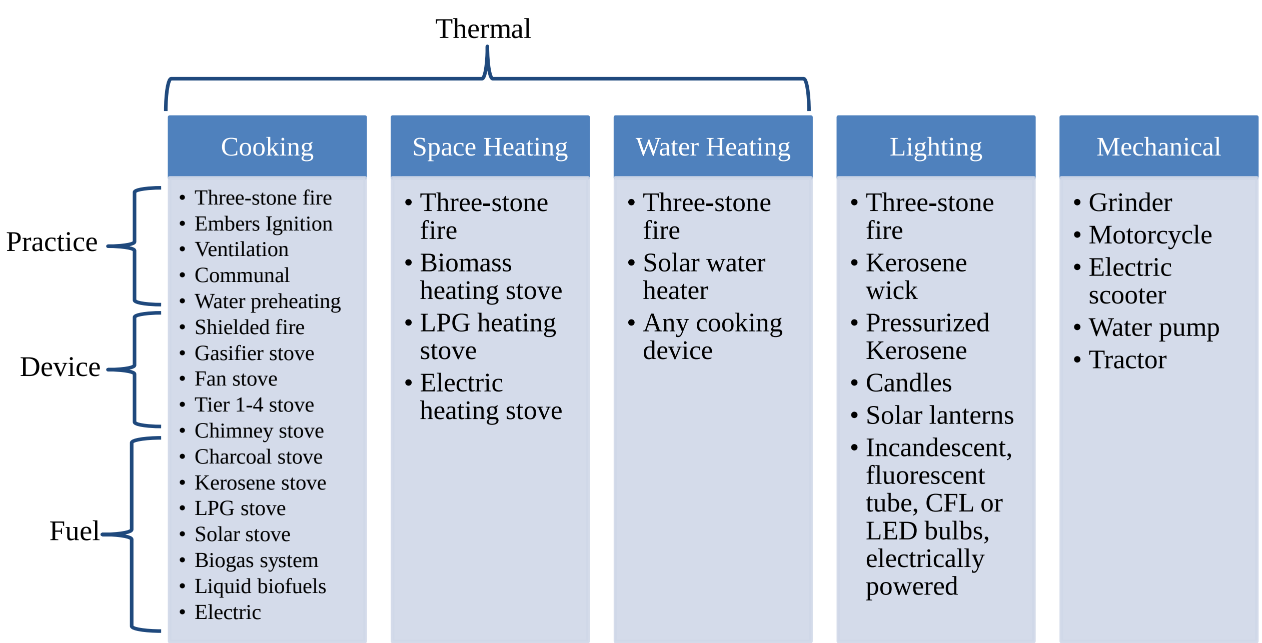

Figure 2.2 Potential technological components

Different components are suited to provide different energy services. These services are divided into the thermal, luminous, and mechanical categories. Thermal devices are used for cooking, space heating, and water heating and require the combustion of fuel, whether solid or otherwise. Lighting energy can be fuel-based from biomass or kerosene, or electricity-based from grid or battery power. And mechanical energy is used to aid in productivity in many forms from transportation to agriculture, mechanized food processing, and pumping water.

In the Malian village, the traditional biomass-fueled open fire is used for 94% of total community energy consumption, with a wide array of applications in both the household and artisanal sectors. In households the traditional fire simultaneously provides cooking, water heating, space heating, and light, as well as secondary benefits such as serving as a central gathering place in the home and providing smoke that seals thatch roofs and protects from insects (Bielecki and Wingenbach, 2014; San et al., 2012). The three-stone fire is free to procure and has been the method of choice for thousands of years. The flexibility of the three-stone fire allows it to accommodate different operational characteristics required by each of the primary residential end uses including higher or lower firepower, vigorous stirring methods, minimal tending, and use of pots of varying size and shape. It varies in efficiency, firepower, and emissions depending on location, application, and use. Similarly, it is these factors that dictate the adoption and outcomes of any alternative energy technologies introduced.

Examples of major types of cookstove technologies for meeting thermal energy needs for cooking, water heating, and space heating include the following:

- “Improved” biomass cookstoves refers to the selection of cookstoves commonly disseminated globally that are expected to offer moderate fuel savings and emissions reductions relative to the three-stone fire. These often take the form of the well-known "rocket" stoves with elbow shaped combustion chambers; there are hundreds of designs that have been implemented over the past several decades. In some cases, operation of cooking stoves differs from that of the traditional fire. The size and type of fuel that the stove can accommodate may require additional time for preparation of the fuel. The frequency of tending during operation is also important as improved cookstoves often require more frequent tending than a heavily-stoked traditional fire, requiring the user to spend more time focusing on fire tending rather than paying attention to other tasks such as preparing the food, fetching water, or caring for children. The capacity and shape of the cookstove dictates the tasks that it can be used for.

- "Advanced" biomass cookstoves designate cookstoves created as a result of the recent efforts to develop cookstoves that offer extremely high efficiency and emissions levels low enough to approach those recently recommended by the World Health Organization (WHO, 2014). An 'Advanced' cookstove is commonly defined as the Tier 4 performance level according to the ISO/IWA 11 "Tiers of Performance", which represents the aspirational and highest levels of performance currently possible for biomass cookstoves including efficiency greater than 40% and emissions near that of LPG (ISO, 2012). This type of cookstove is often highly engineered for specific applications such that optimal performance is limited to a narrow range of firepower and pot size. Several types of cookstove can meet one or more of these performance levels, so discussion throughout this dissertation relies on broad performance levels as opposed to the specific type of stove. Two specific types of stoves with a potential for advanced performance are gasifier stoves that use prepared pelletized fuel with limited primary air and forced draft stoves that use a small electric fan to create mixing and ensure clean burning.

- Biomass cookstoves equipped with a chimney utilize sealed stove bodies to direct heat to the cooking vessel(s) before exiting the kitchen through a chimney in order to help protect health within the kitchen.
- Communal cooking stoves, commonly designed for settings such as schools and hospitals, use large pots (>60 liters) to offer substantial fuel savings. Conducting household cooking communally may be considered acceptable in some communities but not appropriate in others.
- Biomass heating stoves have been developed that hold and radiate heat into the home while removing the emissions through a chimney to address concerns with the traditional use of open heating fires in the household. These unattended fires running continuously are a significant contributor to household air pollution, especially in cooler regions (Baumgartner et al., 2011; Edwards et al., 2007).

In addition to these biomass-fueled technologies, there are a number of alternative fuel-based thermal devices, including both biofuels and fossil fuels:

- Processed biomass such as briquettes or pellets and biofuels, such as ethanol and biogas, are options in areas with sufficient feedstock and a suitable climate. Processed solid fuels are often made from biomass waste, such as dung or crop residue, and can be used in cookstoves specifically designed to burn that type of fuel.
- Charcoal is another form of processed biomass that offers increased energy density and reduced emissions of particulate matter. When charcoal is produced from virgin wood to be used as fuel, roughly 50% of the energy is lost, and emissions are often produced during the production of the charcoal (Pennise et al., 2001). In some cases, leftover charcoal from cooking fires is saved and used later for small tasks, such as steeping tea.

- Biogas is produced locally through the use of a biogas digester in communities where feedstock is available. It comes with the climate advantage of capturing and burning methane, preventing its release into the atmosphere during the natural decomposition process of feedstock such as manure. The slurry leftover after the capture of methane can then be used as fertilizer.
- Fossil fuels such as kerosene or LPG offer high energy density, are cleaner burning, and are convenient to use but have a high associated cost. Due to these high costs and a lack of infrastructure, LPG is not currently available in many rural communities, including the Malian village (Johnson, 2012). In communities where it is available, the cost of cylinder deposit and the relatively high minimum purchase volume of LPG cylinders, or 'lumpiness' of fuel cost, can also be a barrier for low income households, with 25-pound (11.4 kg) cylinders being the most common size used in households (Kojima, Bacon, and Zhou, 2011). With no way to monitor the fuel remaining in a cylinder, to avoid the risk of running out mid-task some households prefer to purchase a second cylinder or use wood during cylinder refill (Heltberg, 2005). Short-weighting of cylinders by adding water or other material, the concept of cylinder ownership, and the dangers associated with poor maintenance of cylinders are additional barriers (Kojima, Bacon, and Zhou, 2011).
- As many targeted communities have abundant solar energy resources, solar thermal systems can be effective. Solar cooking systems include parabolic and panel designs as well as ovens, and they have the same limits due to intermittency as other solar devices. Additionally, they have low energy fluxes and often require considerable change in practice due to long cooking times. Solar water heaters are common in households as income allows due to their convenient and essentially free operation after purchase.

China is now home to an estimated two-thirds of solar heating applications in buildings globally. Most of this is for water heating applications in the form of more than 30 million rooftop water heaters installed in China (Eisentraut, 2014).

Changes in practice can also help to deliver increased energy services. A few possible changes in methods are discussed below:

- Pre-heating water with energy from the sun before placing it on the stove for cooking or washing needs can reduce energy consumption. Many cooking processes involve the heating of water, including boiling of grains and legumes, making medicine, and steeping tea. Andreatta (2014) estimates that pre-heating water to 70˚C can save 50% of the energy required to heat it to boiling point and suggests this can be achieved with various forms of solar collectors, from dark pots with lids to commercially manufactured insulated bags called the AquaPak.
- Energy savings can also be realized after boiling with the use of a retained heat cooker (RHC). An RHC is essentially a well-insulated bag or box in which the cooking pot is placed for a period of time after being removed from the stove. This replaces the simmering process on the stove by using the retained heat to finish cooking.
- Another simple method for saving fuel is saving burning embers to be used to ignite the next fire. This practice was observed in the Malian village and was estimated to save 10% of fuel at a negligible cost (Johnson, 2012).
- Although it does not save energy, increasing ventilation in the home or moving thermal processes outdoors can help to reduce the health impacts of cooking by diluting concentrations of pollutants in the air to which the cook is exposed (Grabow, Still, and Bentson, 2013; Johnson and Chiang, 2015).

- Another possible component is community education regarding the dangers of exposure to household air pollution in an effort to influence behaviors. Some educational campaigns target children in schools to learn the danger and encourage them and their families to limit their exposure to smoke.

Lighting services can be provided by an array of technologies, from fuel-based lighting such as kerosene and candles to electric lighting powered by batteries or an electric grid. Wick-based kerosene lighting is inefficient and polluting (Lam et al., 2012) although this can be improved through the use of a pressurized kerosene lantern. Electric lighting in the home can be provided by many types of bulbs with power from various sources. Available bulbs include incandescent, linear or compact fluorescent, and LED, each offering associated effectiveness, durability, and costs. Electrical power can be supplied by solar home systems, batteries charged in the community or grid or micro-grid if available. Portable lanterns powered by solar charged or disposable batteries are also needed for lighting outside the home. Lighting systems are also important for public venues such as schools and medical clinics.

Mechanical energy services are generally used for productivity. A diesel-powered grinder for grain can complete a task in minutes that would previously have collectively taken hours in the village by hand. Pumping of water can allow access to clean drinking water from aquifers or provide irrigation water to fields. Pumps can be human-powered such as treadle pumps, or electrically-powered mechanical pumps. Mechanized transportation and agricultural services provided by motorbikes and tractors also can increase productivity.

The major goal of this dissertation is to explore the effects of these technological components relative to the baseline scenario. In the Malian village households, the current baseline scenario is defined by the use of the three-stone fire for cooking, specialty cooking processes such as peanut roasting and processing shea. A second fire is used outside for warming water. And heating fires are used indoors near older family members overnight during the cold season. A small traditional charcoal cookstove is used for steeping tea with charcoal leftover from the fires. For lighting, kerosene wick lanterns are used, as are lanterns powered by disposable batteries and community solar-charged battery lighting systems. This dissertation will investigate the effects of incorporating one or more of these alternative technological components into the village energy system to determine which components can offer the most beneficial outcomes in terms of a comprehensive set of objectives. In order to assess these outcomes, there are a number of factors within the system that must also be considered.

2.2 Factors Impacting the Outcome of Village Energy Services

The outcomes offered by these technologies are the result of a complex interaction between the user, the technology, and the energy needs within the system. For example, a cookstove does not save fuel or reduce emissions on its own. It is not the technology the user is seeking but rather the service that it provides. In order for a given technology to effectively provide that service, a user must be inclined and able to procure it, choose to utilize it for one or more tasks in her household, and operate it with the fuel that is available in a manner that is consistent with her needs. These criteria are dictated by a number of parameters including the design characteristics of the technology, conditions under which it is applied, and factors leading to adoption (or rejection) in the village (Figure 2.3). These factors are described in detail below.

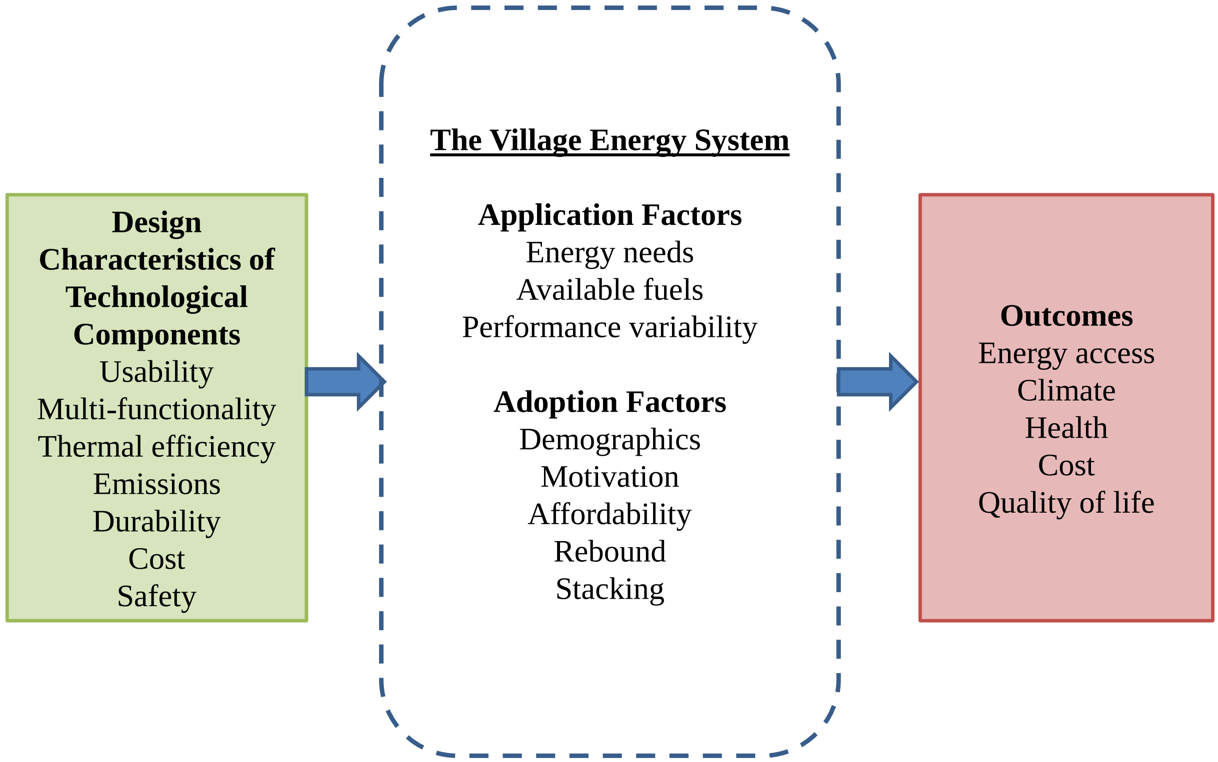

Figure 2.3 Factors in the village energy system

2.2.1 Design characteristics of technological components

There are a number of design characteristics that can be specifically manipulated and optimized when designing an energy service technology for a village energy system.

2.2.1.1 Usability

Balancing technical performance with user compatibility was identified as a primary research need in the cookstove sector by Simon et al. (2014). In the design of any technology that involves interaction with humans, usability is a qualitative concept defined as the effectiveness and satisfaction with which a user can complete a task. Although this definition was taken from the ISO standard 9241 governing the “Ergonomics of human system interaction” aimed at computer user interface design, the principles are applicable to energy systems as well. The definition of usability was expanded by Quesenbery (2001) to include ‘the five E’s’, defining a usable technology as one that is effective, efficient, engaging, error tolerant, and easy to learn.

The effectiveness of a design requires that it be suited to conducting the tasks at hand. In the case of a cookstove this would include cooking, water heating, and/or specialized tasks such as roasting peanuts. For example, an effective design can handle the size and quantity of pots used, accommodate the size and condition of fuels available in a community, and offer the proper level of control of power required. An efficient design in terms of usability does not necessarily refer to thermal efficiency per se, but rather to efficiency in terms of the user’s time and effort for fuel preparation, tending, and operation. An engaging and error tolerant design is enjoyable to use and performs well despite variation in user operation. Finally, usability requires the design be easy to learn and adaptable to any specialized refueling, starting, or operating methods.

2.2.1.2 Multi-functionality

The traditional three-stone fire simultaneously meets energy needs for cooking, warmth, and light, while at the same time meeting additional needs such as serving as a gathering place and producing smoke to ward off insects. Many technologies such as cookstoves limit these additional functions in order to optimize cooking by enclosing the glowing fire, consuming less fuel and therefore producing less heat in the room, and offering cleaner combustion with lower emissions. Because of these limitations to multi-functionality, cookstoves may be used less than anticipated, or the traditional fire may continue to be used alongside the cookstove in order to provide these functions, thus reducing the impact of the new technology (Bilecki and Wingenbach, 2014). Anecdotal evidence suggests that because of this, some devices may not impact net energy use at all (Howells et al., 2005). However, devices can be designed with multi-functionality in mind, whether by retaining some characteristics of the traditional fire or instead by incorporating modern technologies, such as the addition of a thermoelectric generator to charge small electronics. Multi-functionality is important in other energy need categories as well to help optimize impact and adoption, such as designing a lighting system that may also be able to power communication equipment such as radios or cell phones, or providing a multi-functional diesel generator platform to provide grinding, producing electric power, and water pumping services.

2.2.1.3 Efficiency

The technical efficiency of a device is the ratio of the energy delivery to the energy consumption and is a measurable quantity that is determined empirically for technologies. For a thermal device, the thermal efficiency (η) is the ratio of the energy delivered to the food, water, or room to the energy consumed. For lighting, efficiency or effectiveness is the lumens delivered per watt of fuel consumption. There are known design techniques for increasing the efficiency of cookstoves or other energy devices. For example, for cookstoves it is known by general thumb rule as well as in an empirical data set collected from the literature, “stoves with well insulated combustion chambers, pot shields with smaller gaps, and shorter combustion chambers have higher thermal efficiency” (MacCarty and Bryden, 2015). These optimally efficient performance levels often require the use of a single or select few cooking pots for which the stove was designed and a prescribed range of tending and firepower.

2.2.1.4 Emissions

Due to detrimental effects to both health and climate, reducing emissions is often a primary design goal for energy technologies. Emissions are quantified by the measured emission factors (EF), or mass of emissions produced per MJ of fuel consumed or delivered. For example, the ISO IWA has set emissions for cookstoves at tiered levels from 0-4 (ISO, 2011), with a Tier 4, or “advanced”, stove emitting less than 8000 mg/MJ_d of carbon monoxide (CO) and less than 41 mg/MJ_d of respirable particulate matter ($PM_{2.5}$) per MJ of energy delivered to the cooking vessel. More recently, the World Health Organization (WHO) published a strong recommendation for unvented cookstove emission rate targets to protect health as 0.16 g/min for CO and 0.23 mg/min for $PM_{2.5}$ (WHO, 2014). The emissions from biomass combustion can be reduced through a variety of techniques. As seen by stove testing reports that surveyed a variety of stove types (MacCarty, Still, and Ogle, 2010 and Jetter et al., 2012), for example, gasifier-type stoves using prepared fuels such as pellets and forced draft stoves that incorporate small electric fans can both reduce emissions substantially when operating as intended. Emissions produced during the extraction of materials, manufacture, transport, and implementation of any technology may be important as well.

2.2.1.5 Cost

The cost associated with an energy technology consists of purchase and operating costs. Purchase cost is often a key issue in design and is often a trade-off with other factors such as performance, capacity, and durability. The equivalent annual cost of that capital investment is dependent upon the lifetime of the technology, with a longer-lived technology clearly offering a lower annual cost than a short-lived one. It is also a function of the effective discount rate in the household, since a purchase price will appears higher in households with a higher time value of money due to competing pressing needs for the limited funds available. Annual operating costs include maintenance for spare parts and repairs, as well as the costs of fuel, the time to collect that fuel, and the opportunity cost of that time.

2.2.1.6 Durability

The longevity of an energy technology in the often relatively harsh village environment is critical to its success and sustained use. For lighting technologies, durability of bulbs and electronic components is important. For cookstoves, the high temperatures and buildup of soot that takes place during biomass combustion create a harsh environment for materials, and the design choices for these materials directly influence the device lifetime and overall performance and cost. The metal grates and combustion chambers present in many stove designs burn out and require replacement after sustained use. Abrasion and breakage can occur in ceramic combustion chambers. Chimneys clog with soot and require cleaning by the user to function properly. The durability and maintainability of these devices and the availability of spare parts and knowledge dictate the longevity of the impact they offer. It would be counterproductive to implement a technology only to have the product fail prematurely, creating a negative impact and further drain of scarce financial resources if technology is not ultimately used to provide long-term solutions (Henao, 2012).

2.2.1.7 Safety

The safety of a technology is carefully regulated in developed nations and is important in developing communities as well. Alternative fuels such as LPG and ethanol come with safety concerns regarding flammability and leaks. Improved safety of cookstoves can be built into a design with attention to factors such as sharp points, surface temperatures, and containment of combustion. These safety considerations can be evaluated on a scale of 1-4 in terms of ten metrics as recommended by Johnson and Bryden (2015). Electrical devices such as lighting systems should follow safety standards such as that of UL (Underwriters Laboratories). Safety is directly linked to the quality of life offered to the user, and thus the ultimate rate of adoption and sustained use.

2.2.2 Application factors

The in-use performance of an energy technology or strategy depends on the energy needs, available fuels, and performance variability within a community.

2.2.2.1 Energy needs

The energy needs and magnitudes of each need relative to the others is a key factor in the overall performance of a technology as placed in a village. There is a diverse array of varying energy needs across different communities, including cooking processes according to local culture, seasonal rendering of the crops grown in each region, and preparing feed for any livestock that may be present. These needs are met by different types of energy sources, varying tending methods, and a range of cooking implements and vessels. As a result, a technology design will offer differing overall impacts across communities such that a given device may make a large impact in one community but not another. In the Malian village, specialized cooking tasks that represent 8% of domestic energy uses include roasting peanuts and processing shea, among others (Johnson and Bryden, 2012a). In contrast, the additional specialized domestic energy uses measured in a region in Cambodia represent 32% of measured energy consumption and involve burning fuelwood to produce smoke to protect the livestock from insects during the rainy season and preparing food to feed pigs (San et al., 2012). Clearly the optimal village energy strategy in these two areas may differ due to the differing energy services required.

2.2.2.2 Fuel supply

The cost and availability of fuel is a key factor in the decision-making process for energy strategies. In communities where forests are harvested sustainably and wood is abundant the strategies will likely differ from communities where forests are stressed and collection times are increasing. The proximity of a community to urban areas also dictates the cost and availability of LPG, and the presence of livestock dictates whether biogas digesters are an option.

2.2.2.3 Performance variability

The performance of potential technologies is often not well characterized in use in a community. The majority of performance data is taken in the laboratory, which does not necessarily predict performance in the field and often includes a great deal of uncertainty. This uncertainty stems from several areas, including uncertainty in performance testing and uncertainty in use. Testing uncertainty, particularly for cookstoves, stems from (a) uncertainty in instrumentation measurements, a small contribution (~1%), and (b) test-to-test repeatability, a larger source of uncertainty (~99%) (Sutar, 2014). Figure 2.4 shows the range of thermal efficiency measured in the laboratory and reported in the literature for several categories of cookstove type tested at various locations using varying methods. Repeatability is often controlled through the use of laboratory testing where variables such as fuel type, size, and moisture content, pot size, operating style, and cooking cycle are controlled and repeated tests are conducted. This replicability of test results creates a trade-off with the ability to predict performance in the field, however, and it is the performance in the field that ultimately dictates the impact of the technology.

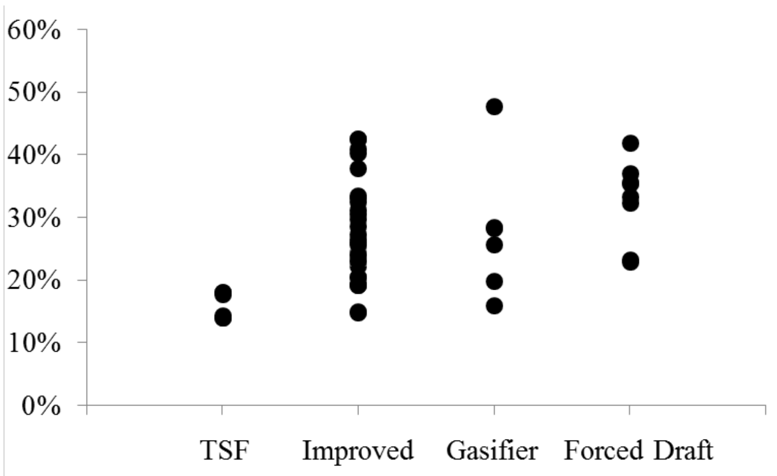

Figure 2.4 Scatter plot of reported thermal efficiency from the literature (for further details see Table 4.2)

Field performance cannot be predicted in the laboratory, is considerably more expensive to procure, and often exhibits significant variability between users and communities. For example, the efficiency and emissions of a cookstove may differ based on the fuel used, whether small twigs, large branches, or even crop residues and dung are used, and the moisture content of the fuel. The method of loading fuel into the combustion chamber makes a difference, as does the frequency of fire tending by the user. Performance also varies based on the application and size/shape of the cooking pot and the conditions under which a device is operated, such as wind, temperature and altitude. In-use variability is also due to changes in performance over time as the product degrades. This myriad of factors makes determining in-field performance with statistical significance difficult. However, it is possible that a precise measure of this performance is not necessary to make decisions between technologies at the village scale. Investigation of the effects of performance and in-use variability on the system-level outcomes may shed light on just how well performance needs to be characterized in order to make decisions, and more research is needed in this area.

2.2.3 Adoption factors

The act of adoption of a new technology is a complex series of conditions and decisions. A synthesis of product diffusion literature and studies of barriers and drivers to adoption of energy technologies, cookstoves in particular, reveals the criteria required for adoption. This synthesis can be categorized as awareness, access, motivation, affordability, and satisfaction (Table 2.2). Assuming awareness and access are provided as part of any program, and therefore focusing on motivation, affordability, and satisfaction, these can be conceptualized as the primary aspects of willingness to adopt. In addition to the choice to adopt or not by a given fraction of the village and the effects of demographic factors on rates of adoption, the behavior changes due to adoption of a new technology are also important. These changes include the rebound effect of increased efficiency and the stacking of fuels and devices.

2.2.3.1 Community demographics

The demographics of a community play an integral role in the adoption and outcomes of any potential technology. Factors such as family size, education, land and non-land assets, and income dictate energy consumption patterns, with the latter three being associated with increased likelihood of adoption of clean cookstoves (Barnes, Khandker, and Samad, 2011). Changes in one or more of these variables may dictate different optimal energy strategies.

Table 2.2 Criteria for adoption

Aspect	Condition	Type	Mechanism
Awareness	Aware of the technology	Social	Marketing, education, word of mouth
Access	Have access to the technology	Technical	Infrastructure
Motivation	Convinced of a need for the technology	Social	Marketing, education, utility
	Convinced of its technical soundness	Technical, Environmental, social	Marketing, social learning, training
	Convinced of its cost effectiveness	Economic	Consumer utility
	Prioritize over other needs	Economic Social	Consumer utility
	Willing to engage in behavior changes required	Social	Education, modernization
	Would like to be insured against the risk of failure	Economic	Warranties
Affordability	Have access to the necessary finances	Economic	Economic development, financing, subsidies
Satisfaction	Sustained use	Technical, Social, Economic, Sustainable	Technical performance, Durability, maintenance

Generated from Slaski and Thurber, 2009; Reddy, 2003; Reddy, Balachandra and Nathan, 2009; Muneer and Mohamed, 2003; Tronsoco, Armendariz and Alatorre, 2013

2.2.3.2 Motivation to adopt

The motivation to adopt was identified as the most important factor leading to adoption of cookstoves by Slaski and Thurber (2009) because even if all other factors are provided for, an unmotivated consumer will not adopt. Motivation includes the requirements that the user be (a) convinced of a need for a technology, (b) convinced of its technical soundness, (c) convinced of its cost effectiveness, (d) prioritize meeting that need over other needs, and (e) be willing to engage in the behavior changes required. The use of ethnography to determine the needs of the community can help to identify the end uses to target and the type of product to offer (Wood and Mattson, 2014), thus ensuring the consumer will recognize a need for the product. Technical soundness is recognized and highly valued by consumers; for example, all successful interventions in a review by Puzzolo et al. (2013) offered affordable, well-designed and quality technology that met users' needs. Perceived technical advantage was also by far the most significant driver of adoption in a measurement of household innovativeness regarding improved cookstove adoption in Sudan (Muneer and Mohamed, 2003).

Social capital and the word of mouth experiences of community members regarding successes or failures of a new technology also significantly impacts motivation. Adrianzen (2014) found a positive empirical correlation between individual improved stove use in Peru and both bonding (inter-communal) and bridging (intra-communal) social capital, defined as the strength of links as measured by trust in community members. Both positive and negative information about operation of the device diffused throughout the communities as social learning through experimentation and learning by doing were shared. They concluded that poor performance or problems with a technology early on will likely result in complete rejection, especially if social capital is strong.

One numeric metric of motivation is deemed 'willingness to pay' (WTP). WTP is generated when a consumer is convinced of their need for the benefits offered by a product, and they outweigh the benefits offered by the current device (Talukdar, Sudhir, and Ainslie, 2002; Mahjan, Muller, and Bass, 1990). This can be modeled as a consumer preference function based on the utility from that service (Bhattacharya, 2011; Larson and Rosen, 2002). Derivation of WTP can be complex, requiring understanding and valuation of benefits offered such as time savings or reduction in indoor air pollution in competition with the multiple risks and needs faced by households in developing countries (Larson and Rosen, 2002). For example, Mobarek et al. (2012) found that women in Bangladesh did not perceive indoor air pollution (IAP) as a significant risk, and found high price sensitivity, low priority, and a low WTP for cookstoves due to reliance on a free traditional technology, which is also noted by Wijayatunga and Attalage in Sri Lanka (2003). A review by Puzzolo et al. (2013) found that time savings in cooking and fuel collection was a recognized benefit although time savings was less valued in rural areas where paid employment is limited. Several studies conclude that strategies should be tailored, such as designing cookstoves with features more highly valued by users (Mobarak et al., 2012) or dissemination should be targeted at populations inclined to be more motivated (Vitali and Vaccari, 2014).

2.2.3.3 Affordability

Ability to pay, or affordability, is also critical such that income is the most frequently studied and significant factor correlated with adoption of clean stoves and fuels (Lewis, 2012). Factors such as purchase price of equipment, magnitude and “lumpiness” of ongoing fuel supply and maintenance costs, and liquidity- or credit-constraints in poor households dictate the consumer’s ability to pay. Long term services including initial investment and operating costs are compared in terms of Net Present Value (NPV) by discounting future costs at a given “risk-free” interest rate or social planner’s discount rate. This is most commonly analyzed at a default of 5% by assuming sufficient cash reserves for the initial investment. However, in liquidity-constrained households the perceived rate is often much higher due to the lack of disposable or saved cash during the (typically short) budgeting period and the high costs of loans even when available. A review of empirical private implicit discount rates (IDRs) for energy appliances found rates as high as 90%, and a fitted discount rate for income quintiles in low income rural communities in India showed a discount rate of 74% for low income households (Ekholm et al., 2010). Affordability factors can be affected by policy or assistance such as subsidies and microfinance. Direct subsidies of the cookstove or fuel are important for equity of access if properly targeted. However, the management of subsidies is complex, and care must be taken to avoid adverse effects on markets and perceived value of the technology (Puzzolo, 2013) and to avoid encouraging over-use (Jeuland and Pattanayak, 2012).

2.2.3.4 Rebound

First introduced as ‘Jevons paradox’ in 1865, the rebound or “take-back” effect occurs when the anticipated savings due to increased energy efficiency are ‘taken back’ by increased use of that energy service. It results from the increased fuel, time, and income provided by energy savings, which lead to increased consumption. This effect is modeled as a function of the change in efficiency of the new devices and the economic fuel price elasticity factors. This is well characterized in other sectors, for example, the increase in demand for vehicle miles traveled resulting from an increase in vehicle fuel efficiency. Although rebound is often low in developed countries, in developing nations where there is a high level of unmet demand, the rebound effect can be quite high due to suppressed demand (Roy, 2000). Thus rebound is an important factor to consider with respect to energy services because it provides an increase in delivered energy but reduces anticipated fuel savings and emissions reductions.

2.2.3.5 Stacking

Biomass, such as fuelwood, has been a primary source of energy for humankind for at least 500,000 and as many as 1.7 million years, and biomass continues to supply approximately 10% of global primary energy today (James et al., 1989; IEA, 2014). However as income, inclination, and infrastructure in communities allow, traditional fuels and devices are gradually replaced with those offering increased convenience, cleanliness, and energy density. This occurs as a gradual transition that includes use of multiple fuels, or fuel stacking, as opposed to linear steps between fuels with former fuels being abandoned (Masera, Saatkamp, and Kammen, 2000). For example, non-solid fuels such as LPG may first be used for preparing tea or quick/small cooking tasks while the remainder of thermal tasks are supplied by biomass, with gradual replacement as income allows. Often new fuels or devices do not suit the needs or cultural preferences for specific tasks, for example users find it difficult to prepare tortillas using LPG cookstoves (Masera, Saatkamp, and Kammen, 2000), or factors such as the belief that food cooked in a clay pot with biomass tastes better than that of food prepared with more efficient fuels or pots (Wijayatunga and Attalage, 2003). Similar to fuel stacking, device stacking occurs when new technologies such as cookstoves are used alongside traditional devices as opposed to replacing them completely. Factors that lead to fuel and device stacking include the previously discussed factors of convenience, suitability, and multi-functionality. Stacking also results from the capacity factor of renewable technologies, such as reverting to the use of traditional methods on days the sun is not powering batteries or solar thermal devices. Due to these factors, the relative advantages of each option should be assessed and adoption measured and modeled separately for each task in order to avoid over estimation of the benefits of interventions, which has occurred in the past (Ruiz-Mercado et al., 2011; Masera, Saatkamp, and Kammen, 2000).

2.3 Objectives and Outcomes of Village Energy Service Strategies

Although the three-stone fire is flexible, free, and familiar, its continuing use for hours each day in hundreds of millions of rural households is inefficient and polluting. The 2010 global burden of disease report estimated 4 million premature deaths each year can be attributed to the household air pollution (HAP) created by the combustion of solid fuels for cooking, primarily due to exposure to fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO). This makes HAP the fourth leading cause of death globally (second for women) behind only diseases related to obesity, cigarette smoking, and alcohol consumption (Lim et al., 2012). Residential biomass combustion is estimated to be responsible for 25% of the global black carbon emissions inventory, a pollutant approximately 910 times stronger than carbon dioxide which creates serious impacts on the climate and accelerates glacial melting (Bond et al., 2013). The collection and use of biomass fuel, especially in areas with retreating forests, takes time and energy, and creates drudgery and safety concerns for users. The use of open fires poses safety risks to users and children, who are often in the kitchen alongside their mother.

The rewards of meeting these needs for energy services while reducing the negative impacts are great. Not only will the implementation of sustainable energy services help to reduce the challenges involved to simply meet needs for basic survival, the availability of energy to conduct productive uses has the potential to make a “tremendous impact” on health, education, and gender equality (Cabraal, Barnes, and Agarwal, 2005). Comprehensive development goals such as this require attention to more than simply the technical issues associated with energy system design. The UNDP defines sustainable energy services as “energy produced and used in ways that support human development in all its social, economic and environmental dimensions” (UNDP, 2000). It is these dimensions, which go beyond the technical challenges, that led the UK

Department for International Development (DFID, 2002) to call for “taking a people centered approach... to deliver energy services that meet peoples’ needs and priorities” as well as “taking an holistic approach to energy rather than a project based approach.” As a result, this research seeks to evaluate potential energy system design strategies in terms of a comprehensive set of objectives, each measured by a number of outcomes (Table 2.3). These include

1) Minimization of primary energy consumption and forest harvest rate, with maximization of useful energy delivered and the quantity of services provided
2) A decrease in impacts to climate through a reduction of the greenhouse gases emitted from combustion and production including the Kyoto gases as well as other species of interest to biomass combustion such as black carbon
3) A reduction of health impacts by lowering human exposure to health-harming pollutants such as carbon monoxide (CO) and fine particulate matter ($PM_{2.5}$)
4) A minimization of costs, both financial and opportunity, and upfront and ongoing, to both the user and implementer in terms of an annual investment over the lifetime of the analysis as well as incremental costs of other impacts
5) Improvement in the social aspects of the quality of life of the user in terms of safety, desirability, convenience, and change in practice required by the use of the technology

Table 2.3 Objectives and outcomes of energy services

Objective	Energy Access	Environment	Health	Economic	Social
Outcome	Energy delivered	Climate	Exposure	User Costs	Disruption
	Energy consumed	Forest harvest rate	-CO	-Purchase	Desirability
	-Primary		-PM	-Maintenance	Convenience
	-Renewable			-Fuel	Safety
				-Time	
				Subsidy	
				Implementation	
				Infrastructure	

Although all of these outcomes are important at some level, it is important to consider also that the valuation of priorities often differ between stakeholders at different scales. Complexities and failures often arise when objectives conflict. For example, a highly efficient device that preserves forests may not be convenient to use, or a low-emissions device that slows global climate change may be too expensive for the user. Yet ultimately a compromise strategy that meets the needs of the users, implementers, and development organizations is required for success.

The development and evaluation of such a strategy is investigated in the chapters that follow. Chapter 3 will explore how these outcomes have been modeled by previous researchers, and Chapter 4 will present a comprehensive model of the village energy system including the design choices, system-level factors, and outcomes.

CHAPTER 3

ENERGY SYSTEMS MODELING

Computer-based modeling is frequently used to assist with the design of energy systems. A variety of models have been widely used for the design of power generation strategies in both the developed and developing world, but fewer models have been applied to the mix of technologies, end use energy needs, and factors specific to off-grid rural villages. Some existing models, however, have addressed various issues that are applicable in part to village energy. As shown in Table 3.1, there are a variety of existing models that cover areas within the energy types, analysis goals, factors involved, and objectives needed to model rural energy systems. The type of energy modeled is catalogued because as previously mentioned, often existing models have focused on the need for electrical power although thermal energy represents the most significant energy need in villages. The method of analysis also indicates the utility and level of detail expected, from specific cost-benefit analyses (CBA) to broad 20-year forecasts. The number of factors included in a model indicates how accurately the model may reflect the complexities of the energy system. And the objectives covered indicate how heavily the analysis focuses on a single objective or two, or whether a holistic picture of the needs of all stakeholders is provided.

The models in Table 3.1 are further divided into four categories, organized from the broad topic of energy and villages to the specific methodology and factors or objectives involved. These are (a) energy modeling packages, (b) conceptual frameworks for rural energy, (c) multi-criteria decision analysis applied to given scenarios, and (d) methodologies for determining specific parameters or outcomes to report. Energy modeling packages are commercial software that allow for simulation, forecasting, and optimization of energy systems at a broad scale. Conceptual frameworks involve discussion and in some cases modeling that delineates the layers of objectives, stakeholders, energy needs, and constraints specific to a village energy system. Multi-criteria decision analysis (MCDA) is a family of modeling methodology used to analyze systems with multiple objectives and is applicable to a wide range of fields, which in this case involves models written based on MCDA methods used to analyze energy systems. Finally, studies that modeled specific factors and objectives relevant to components needed in the overall rural energy system are included. The models within these categories are reviewed in the following sections.

3.1 Energy Modeling Packages

A number of existing modeling packages are available for energy systems, many of which are reviewed by Urban, Benders, and Moll (2007) and Van Ruijven et al., (2008). Some of these have been applied in the context of electrical and thermal energy for off-grid villages in developing nations. These are reviewed in the order of most to least specific to village thermal energy needs.

Long-range Energy Alternatives Planning (LEAP) is a modeling and scenario forecasting tool that simulates quantity, costs, and emissions of energy including consumption, production, and resource extraction based on both demand and supply sides (SEI, 2015). Limmeechokchai and Chawana (2007) applied LEAP to assess energy consumption and emissions reductions for improved cookstoves and small biogas digesters for cooking and lighting in rural Thailand using assumed adoption rates and emission factors from the literature. They predicted that biomass

Table 3.1 Summary of existing models

Study	Model Family	Energy				Analysis					Factors									Objectives							
		Thermal	Electricity	Light	Mechanical	Simulation	Optimization	Forecasting	CBA	Sensitivity	Appliance	Fuel	Practice	Subsidies	LCA	Rebound	Opportunity Cost	Stakeholders	Participation	Energy Eff.	Economic	Environment	Health	Social	Institutions	Equity	Sustainability
<u>Energy Modeling Packages</u>																											
Paleta, 2012	HOMER		x	x			x				x	x								x	x						
Johnson, 2013	HOMER			x		x	x			x	x									x	x						
Mustonen, 2010	LEAP					x														x	x	x					
Limmeechokchai, 2007	LEAP,AHP, CBA	x		x		x		x	x	x	x	x						x		x	x	x		x			
Howells, 2005	MARKAL	x	x	x			x				x	x								x	x	x					
Ekholm, 2010	MESSAGE	x					x	x		x		x		x			x				x					x	
Byrne, 1998; 2007	RREAD		x			x		x			x									x	x			x		x	
<u>Conceptual Frameworks for Rural Energy</u>																											
Cherni, 2007	ITDG+SUR EDSS		x			x														x	x	x		x	x		
Henao, 2012	SURE-DSS		x			x		x												x	x	x		x			x
<u>Multi-Criteria Decision Analysis</u>																											
Kanagawa 2007	META-Net	x	x	x			x	x			x	x					x			x	x		x	x			
Georgopoulou, 1997	ELECTRE III		x			x				x	x	x						x	x	x	x	x		x			x
Silva, 2009	GP		x			x				x		x								x	x	x		x		x	
Ramanathan 1994	GP	x					x			x	x	x			x					x	x	x		x			x
Ramanathan 1995	AHP-GP			x			x			x					x					x	x	x		x			x
Beccali, 1998	Fuzzy+ELECTRE	x	x	x			x				x	x								x	x	x		x			x
Jinturkar, 2011	Fuzzy GP	x					x					x									x	x		x			x
Gaul, 2013	Life cycle	x	x	x	x	x				x	x	x			x		x			x	x						

Table 3.1 Continued

	Model Family	Thermal	Electricity	Light	Mechanical	Simulation	Optimization	Forecasting	CBA	Sensitivity	Appliance	Fuel	Practice	Subsidies	LCA	Rebound	Opportunity Cost	Stakeholders	Participation	Energy Eff.	Economic	Environment	Health	Social	Institutions	Equity	Sustainability
<u>Single Aspects</u>																											
Biswas, 2001	Biogas CBA	x				x			x	x		x									x	x				x	x
Ravindranath, 2006	Abatement cost	x	x	x		x					x	x									x	x					
Wilkinson, 2009	Health & Climate	x				x		x			x		x									x	x				
Mestl, 2007	Health impacts	x				x						x											x				
Larson, 2002	Health valuation					x															x		x				
Grieshop, 2011	Health & Climate	x									x	x										x	x				
Banerjee, 2011	Exergoenvironmental	x	x	x		x				x	x	x			x					x	x	x					
Spalding-Fecher, 2002	Benefit analysis	x		x		x					x					x				x	x	x					
L'Orange, 2013	Monte Carlo	x				x				x	x									x		x	x				
Yu, 2011	Benefit analysis	x									x		x								x		x				
Rubab, 1996	Linear programming	x					x					x								x	x						
Reddy, 1996	Predator-Prey					x		x			x	x															
Mink, 2010	economic viability	x							x	x				x							x						
Jeuland, 2012	Monte Carlo CBA	x				x			x	x	x	x		x			x			x	x	x		x			
Mehta, 2004	Benefit analysis								x		x	x	x								x	x	x				
Hutton, 2007	CBA	x							x								x										
Garcia-Frapolli, 2010	CBA	x							x	x											x	x	x	x			x
Johnson, 2012	Fuel Use	x				x					x		x							x	x						
Aunan, 2013	Monte Carlo CBA	x				x			x	x											x		x				

cookstoves could reduce energy consumption by 1.17 million TJ and climate impact by 10 million tCO_{2e} through 2030 at a cost of \$0.95/tCO_{2e}, and biogas digesters could reduce LPG consumption by 242,000 TJ and mitigate 1.5 million tCO_{2e} over the period from 2002 to 2030. They also indicated that the barriers to adoption involve a lack of capital, information, and skilled labor. Mustonen (2010) used structured interviews applied to the LEAP model to analyze scenarios for three levels of rural electrification in Lao People's Democratic Republic: residential demand, income generation, and public services. The latter two scenarios assumed adoption of improved cookstoves by 48% and 86% of electrified households, respectively. They analyzed the levels of electrification in terms of the Millennium Development Goals, qualitatively discussing the effects of electricity generation scenarios on income generation and expanded public service and the resulting impacts on education, gender equality, and health. Shortcomings of the LEAP model include a focus primarily on technical, economic, and climate dimensions but serves as a tool that offers analysis of complex energy systems from both the supply and demand sides across sectors that allows for policy analysis and tracking of energy consumption, production, and extraction as well as both local and regional air pollutants.

Kanagawa and Nakata (2007) used the bottom-up 'META-Net' economic modeling system jointly developed by Lawrence Livermore National Laboratory and Tohoku University to analyze wood versus gas cooking forecasts in India in terms of health and economic metrics including 5 end-uses, 28 technologies, and 7 markets as inputs. They include opportunity cost of fuelwood collection and assume the total energy demand increases linearly at the 1.4% growth rate of India. The model was reasonably comprehensive in terms of objectives and suited to energy uses in rural villages, but did not consider factors such as rebound, life cycle, user participation, or social considerations.

The Market Allocation (MARKAL) model and TIMES, MARKAL's extension for modeling of time of day load curves, were developed by IEA's Energy Technology Systems Analysis Programme as a multi-priority least-cost linear optimization model to evaluate energy and technology choices. Howells et al. (2005) used MARKAL/TIMES model to compute optimal energy systems for disaggregated devices, fuels, and end uses in a non-electrified rural village in South Africa. They modeled load curves of six major end uses (cooking, heating, water heating, lighting, refrigeration, and other), a range of inputs to generate electricity (renewable, converted, and imported), and 22 end use appliances using input data from a survey designed specifically for energy systems modeling. Scenarios included baseline, stand-alone generation only, grid electrification, electrification with cost reflective pricing, and externalities to include the health costs of emissions. Several novel, important concepts were included, such as load curves and demand side management, the multi-functionality of some devices, user behavior and preferences as constraints to the model, and pollutants and safety hazards as externalities. However the focus was primarily economic and based on electrification scenarios, and therefore neglected the array of other potential technologies as well as the social and other objectives.

The MESSAGE (model for energy supply strategy alternatives and their general environmental impact) framework developed by Messner and Strubegger (1995) and IIASA (2013) uses linear cost optimization for scenario forecasting for disaggregated consumer groups and considers discount rates and inconvenience costs. Ekholm et al. (2010) used MESSAGE combined with a microeconomic fuel choice model to forecast national energy consumption by type (e.g., biomass, LPG, kerosene, and coal) with adaptations to account for differing discount rates for separate urban and rural consumer income groups modeled from national survey data on household energy consumption from India. The fuel choice model included price and technological parameters, discount rates, inconvenience costs, collection time, and household budget. It was used to illustrate the impacts of strategies targeting cost-related variables, such as subsidies, financing, and lowering inconvenience costs on the fuel mix at a national scale. The authors noted the model will be less effective at addressing specific needs at the household level because linear cost optimization reports a single solution although households will likely choose to use multiple fuels.

Byrne et al. (1998) developed Rural Renewable Energy Analysis and Design (RREAD) as a spreadsheet model to process resource, technology, economic, and policy data. They examined four options for small rural off-grid wind and PV and traditional petroleum electric power generation technologies in China. Inputs included the renewable resource profile, household load data, system configuration, costs, financial data, and policy scenarios. Outputs included energy metrics, net present and levelized costs, and sensitivity analyses. A later paper (Byrne et al., 2007) investigated over twenty configurations including lifecycle analysis, socioeconomic assessment with logit modeling to determine market potential, GIS classification, and livelihoods assessment. Socioeconomic regression suggested household income vs expenses, size, and housing area as predictors of which system a household is likely to favor. Although this model was fairly comprehensive regarding objectives, it omitted thermal energy.

The Hybrid Optimization Model for Electric Renewables (HOMER) software developed by the US National Renewable Energy Laboratory (Homer Energy, 2015) optimizes the technical and economic objectives of stand-alone power generation given load profiles and a menu of generation and storage options. Paleta, Pina, and Silva (2012) used HOMER to optimize remote autonomous electricity generation systems for household, school, and health center sectors, accounting for demand growth considering a hybrid system and a fully renewable PV system. Johnson, Glassmire, and Lilienthal (2013) used HOMER to analyze options for rural lighting including centralized grid electrification, battery charging centers, and solar lanterns. The methodology for simulation, optimization, and sensitivity analyses used by HOMER is illustrative by allowing for analysis of a variety of components and associated parameters. Yet its application to rural developing community energy systems is limited by a focus only on technical and economic objectives and its provision for the design of electrical power generation only.

3.2 Conceptual Frameworks for Rural Energy

Several conceptual frameworks of village development systems have been introduced to analyze a broad picture of the effects of energy and other developments while considering the objectives, stakeholders, needs, and constraints specific to a village system. For example, a people-centered approach to ensure sustainability of common pool resources was developed by Practical Action in the “Energy for Rural Livelihoods: A Framework for Sustainable Decision Making” manual (Mulugetta et al., 2005). They asserted that communities possess five measurable types of capital or resources: physical, financial, natural, social, and human, which encompass five “spheres” of objectives: energy services and technology, economic and financial, social development, environmental and resource, and institutional (Cherni et al., 2007). The framework is especially concerned with user participation, supportive institutions, and choice of technology through careful analyses of multiple factors. The multi-criteria decision modeling software package called Sustainable Rural Energy Decision-Support System (SURE-DSS) was developed based in part upon this framework and involves a comprehensive assessment of local and regional conditions prior to the introduction of energy systems. It also evaluates technology choice based on their impact on four of the five Intermediate Technology Development Group (ITDG) objectives (technical, financial, environmental, and social) and includes human impacts. The analysis assesses strengths and weaknesses of a community before and after intervention in terms of the five types of assets and then seeks to optimize impacts on each by minimizing the distance from the “ideal” level while considering the minimum aspiration level in the community (Brent and Kruger, 2009; Cherni, 2005; Cherni et al., 2007). Both frameworks are used to facilitate planned infrastructure with the long term goal of enhancement of rural livelihoods through qualitative evaluations of five “spheres” of objectives and capital in a village, but they lack quantitative analysis.

3.3 Multi-Criteria Decision Analysis

Multi-criteria decision analysis methodologies have been used in a variety of studies to analyze several aspects of energy services. In addition to cost-benefit analysis, these include the analytical hierarchy process (AHP) pair-wise comparison, which is used to prioritize alternatives associated with objectives, goal programming (GP) which seeks to minimize the deviations from set goals for objectives, the ELECTRE family of outranking approaches, and algorithms based on biological systems. Pohekar and Ramachandran (2004) reviewed methods based on weighted averages, priority setting, outranking, fuzzy principles, and their application to sustainable rural energy planning, and they found that Analytical Hierarchy Process is the most popular technique followed by PROMETHEE and ELECTRE.

CBA is frequently used by monetizing outcomes of various objectives and comparing cost effectiveness in terms of device, fuel and implementation costs, and cost per household of potential scenarios. CBA was used by a number of studies (Hutton, Rehfuess, and Tediosi 2007;

Limmeechokchai and Chawana, 2007; Biswas, Bryce and Diesendorf, 2001; Mink, 2010; Jeuland, 2012; Garcia-Frapolli, 2010; Aunan, 2013; Mehta, 2004).-Assigning monetary benefits to users or representing as economic externalities factors such as health, carbon, and time in the form of cost-benefit analyses is possible; however, it is not always preferred for several reasons. First, it can lead to estimates higher than actual benefits because direct financial benefits to the household do not automatically result from improvements to health or climate (Mink, 2010). Second, going rates for carbon, for example, do not presently account for non-Kyoto emissions, which play a significant role. And finally, aspects such as time and health are a value within themselves, especially in informal, non-commercial rural economies such as those in rural developing villages.

Ramanathan and Ganesh (1994, 1995) conducted a general multi-criteria optimization as well as an integrated GP-AHP model for cooking and lighting using multiple energy sources and 9 to 12 weighted objectives including maximization of system efficiency, employment generation, use of locally and long term available sources, convenience, and safety with concurrent minimization of fuelwood, emissions, and life cycle cost. They used AHP to assign coefficients to qualitative criteria, and sensitivity analysis was provided. Silva and Nakata (2009) used GP for optimization of rural electrification with renewable energy systems in Columbia with four goals and four priority structures. They predicted costs, land use, environmental benefits and employment generation. Their analysis proposed that the substitution of biomass with electricity would raise household energy expenditures by two to five times their present values.

Fuzzy programming and the ELECTRE method family can be used to account for uncertainty, the qualitative nature of some indices, and weighting for multiple objectives. These techniques were used by Georgopoulou, Lalas and Papagiannakis (1997) and Beccali, Cellura, and Ardente (1998) to model renewable power generation on remote Mediterranean islands. Georgopoulou, Lalas and Papagiannakis (1997) identified multiple stakeholders, selected a number of quantitative and qualitative objectives, formulated eight strategies, and applied the method with analysis of results and stakeholders' reactions on a scale of impact. Beccali, Cellura, and Ardente (1998) used indifference, strict preference, and veto thresholds to consider 14 different technologies/energy sources and 12 objectives within three scenarios, including environmental-oriented, economic-profit oriented, and energy savings and rationalization scenarios. Jinturkar and Deshmukh (2011) used fuzzy mixed integer goal programming to model cooking and heating energy strategies with uncertainty to consider the four scenarios separately to optimize the objectives of cost, emissions, social acceptance, and utilization of local resources.

3.4 Single Aspects

Methods to quantify outcomes in terms of specific technical, environmental, social, and economic objectives have been addressed by a number of studies.

3.4.1 Environmental impacts

Environmental effects are most commonly reported in terms of greenhouse gas emissions as tons of carbon dioxide equivalent (tCO_{2e}). This measure of global warming commitment (GWC) is determined by the carbon dioxide (CO_2) emissions from combustion plus the emissions of each product of incomplete combustion weighted by its global warming potential (Table 3.2). Long-lived gases including CO_2, methane (CH_4), and nitrous oxide (N_2O) are a key focus in the Kyoto protocol and are currently tradable through the Clean Development

Mechanism (CDM) and carbon markets, whereas shorter-lived gases and aerosols such as carbon monoxide (CO), non-methane hydrocarbons (NMHC), black carbon (BC), and organic carbon (OC) are not but are important for fuel combustion activities. Often analyses consider the GWC with the non-Kyoto emissions (Grieshop, Marshall, and Kandlikar, 2011; Jeuland and Pattanayak, 2012) or without in the cases of economic, market-value analyses based on carbon financing models (Hutton, Rehfuess and Tediosi, 2007). Analyses are commonly conducted with either 20 or 100 year time periods, with 100 years used in the Kyoto protocol; however, Smith et al. (2000) argued in favor of the 20-year scale for rural energy development programs because use of longer time horizons would penalize near generations for the benefit of later ones. As shown by Table 3.2, the weighting of many of the products of incomplete combustion is heavier in the shorter time scale than the longer.

Table 3.2 Global warming potential

Emission	GWP_{20}	GWP_{100}
CO_2	1	1
CH_4	72	25
N_2O	289	298
CO	10	1.9
NMHC	4.9	3.4
BC	3200	910
OC	-250	-75

Forester et al., 2007; Bond, Venkataraman, and Masera 2004; Bond et al., 2013

An additional environmental effect is the sustainability of the forests. Forest harvest rate can be determined through fuel use analyses. The additional environmental effect of reduced deforestation is considered by Hutton, Rehfuess, and Tediosi (2007) and Jeuland and Pattanayak, (2012), calculated as the replacement cost and market value of the trees, respectively.

3.4.2 Health impacts

Prediction of health impacts is challenging due to the number of confounding variables between quantities that are measurable and those that are of interest. This range of variables includes the mass rate of emissions released from combustion, the spatial and temporal air quality due to cooking procedures and household ventilation, the inhaled fraction due to personal respiration rate and location, the biomarkers of exposure, and ultimately the desired metric, the health response to the ingested pollutant. This uncertainty between measurable pollutant emissions and unmeasurable health outcomes poses a significant research challenge. In addition, DuFlo, Greenstone, and Hanna (2008) points out that if there is less smoke near the improved cookstove, the members of the household may choose to spend more time near it than before, ultimately reducing the impact or even increasing their exposure to pollutants. Clark et al. (2013) provided a summary of the advantages and disadvantages of various exposure assessment methods, concluding that none currently offer acceptable levels of uncertainty.

With awareness of this challenge, previous models have used a variety of methods to model health impacts of energy interventions. Johnson et al. (2011) used a Monte Carlo single-box model to predict indoor air concentrations of pollutants as a function of stove emission rate and air exchange rate. Kanagawa and Nakata (2007) computed average daily exposure based on concentration and time allocation studies, and Grieshop, Marshall and Kandlikar (2011) estimated personal daily intake based on published emission factors. Similarly, L'Orange (2013) compared exposure, dose, and the resulting relative risk of death from empirical emission rates and estimated the corresponding investment required to save one life. Wilkinson et al. (2009) used an adaptation of the Comparative Risk Assessment methods based on concentration and

World Health Organization (WHO) models to estimate that 2.4 million premature deaths could be averted in India by 2020 through fuel switching and improved cookstoves. Mestl, Aunan and Seip (2007) developed population weighted exposure metrics and argued the fuel-based methodology used by the WHO to estimate morbidity and mortality underestimates the actual health effects. They suggest an alternative exposure assessment methodology, and they estimate the effects of changes in cooking fuels in households in three partial to full fuel-switching scenarios. Aunan et al. (2013) then used empirical data from China including concentration and time-activity patterns to estimate avoided cases of chronic obstructive pulmonary disease (COPD). Most recently, the World Health Organization (WHO) published a 'strong' recommendation for unvented cookstove emission rate targets to protect health based on a Monte Carlo analysis of a single zone box model of a typical kitchen size, ventilation, and cooking duration (WHO, 2014). Finally, Smith (1994) used the Relative Hazard Index (RHI) to aggregate and compare the quantity of air required to dilute the pollutants to levels deemed safe by air quality guidelines (AQG).

Monetization of health impacts requires a second level of assumptions for quantitative reporting of health effects. Larson and Rosen (2002) calculated the utility of IAP reductions to households in terms of the shadow price of improved adult health, which includes five terms, including "pain and suffering", avoided expense, increased productivity, and indirect effects for adults and children. Howells et al. (2005) modeled health impacts as externalities in TIMES using a monetary value per ton for five pollutants taken from the literature. Hutton, Rehfuess and Tediosi (2007) calculated health care cost savings and productivity gains valued at gross national income (GNI) per capita due to improved health impacts using three personal exposure field studies of stoves with chimneys. Garcia-Frapolli et al. (2010) calculated avoided costs in the household, avoided government spending on healthcare for respiratory diseases, and time saved as a result of better health. Jeuland and Pattanayak (2012) determined the economic cost of morbidity using the cost-of-illness (COI) per case, which includes cost of treatment, patient costs, and lost productivity costs. These were based on the expected reduction in cases for acute respiratory infection (ARI) and for chronic obstructive pulmonary disease (COPD) where costs are discounted by the number of years to disease onset. They also applied the expected risk of death and value of a statistical life for mortality calculations. Finally, Aunan et al. (2013) used a Monte Carlo simulation to calculate the value of avoided cases of COPD relative to intervention cost.

3.4.3 Economic metrics

Economic metrics involve both upfront investment costs and ongoing costs of operation and are a function of the useful life of the technology and the economic situation of the household and community, as well as the impacts of any programmatic strategies such as subsides. Johnson (2012) used energy use data from the Malian village to compute the equivalent annual investment cost for several devices including four types of improved cookstoves and solar water heaters. Ravindranath et al. (2006) provided a comparison of the incremental cost of carbon abatement for ten combinations of bioenergy technologies for cooking and power generation using life cycle costing methods. Ekholm et al. (2010) used econometric modeling to investigate several future scenarios to explore policy mechanisms such as fuel subsidies and micro-financing in India based on consumer discount rate. And Mink (2010) developed an economic “cookstove calculator” that, when paired with a brief socioeconomic survey, was used to identify the feasibility of improved cookstoves for a family in terms of NPV, internal rate of return (IRR), and CBA during the market generation phase.

3.4.4 Time savings and opportunity costs

Opportunity costs result from the time spent, primarily by women and children, to collect and prepare fuel and cook that could otherwise be theoretically spent in income-generating, agricultural, or educational activities. Reddy et al. (2009) estimated the 82 million hours per day spent collecting fuelwood in India alone results in an economic burden of time and illnesses of 300 billion rupees (5 billion dollars) per year. Gaye (2007) found a strong correlation between the time children in Malawi spent collecting fuel and reduced school attendance, as evidenced by lower literacy levels in fuelwood stressed regions of the country. However, one might argue in some cases that the number of hours spent by children to collect fuel each week (e.g., 40 hours per year per child in the Malian village reported in Johnson and Bryden, 2012a) may not significantly impact time available for education.

The opportunity cost of time is modeled as the product of the quantity and value of that time, with the time required for collection and preparation of fuel determined empirically. The value of time accounting for lost income generating opportunity is a product of the local wage rate and the ‘shadow value’ of time. The shadow value is used to account for cases where paid opportunities are not necessarily available during that time. Jeuland and Pattanayak (2012) set the shadow value at low, mid, and high levels of 0.1, 0.3, or 0.5 times the hourly wage rate. The local unskilled labor rate must be determined through surveys or other methods. Kanagawa and Nakata (2007) estimated the daily or hourly wage rate as a fraction of women’s hourly contribution to the household income. The cost of reduced time for education is more difficult to quantify as it is a function of lost future wages due to a lower educational attainment (Banerjee and Tierney, 2011). Ekholm et al. (2010) note there is also a direct monetary opportunity cost of using freely gathered fuels due to the presence of the traditional fuel market, suggesting the price of the fuel is significant for the gatherers and should reflect the time needed for gathering. Opportunity costs are also addressed by Hutton, Rehfuess, and Tediosi (2007) and Garcia-Frapolli et al. (2010).

3.4.5 Rebound

With the exception of the model by Spalding-Fecher et al. (2002), the change in fuel consumption resulting from improved devices such as cookstoves has been predicted exclusively as directly proportional to the change in fuel efficiency. This approach accounts only for first order effects. In a more comprehensive analysis, the savings are also a direct function of the increased income available due to energy savings, which leads to increased consumption, as well as an indirect function of long-term changes in household behavior regarding energy use.

Direct rebound is measured as the fraction of energy savings retaken by increased demand. For example, if an energy service device with increased efficiency would theoretically reduce annual energy use from 100 MJ to 90 MJ but when measured is found to reduce to only 91 MJ, the rebound effect was 1 MJ out of 10 MJ or 10%. This direct rebound effect, postulated by Khazoom (1980) as described by Berkhout, Muskens, and Velthuijsen (2000), is predicted using measures of efficiency improvement, $\Delta\eta$, and the energy cost (price) elasticity of demand for energy services, β:

$$\frac{AEU_{i,j,post}}{AEU_{i,pre}} = \Delta\eta_{j_{post}-j_{pre}}\left(-\beta_{fuel}-1\right)+1 \tag{1}$$

The change in efficiency is determined empirically, and the fuel price elasticity is determined through econometric analyses of fuelwood supply and demand in a community; this relationship is shown in Figure 3.1.

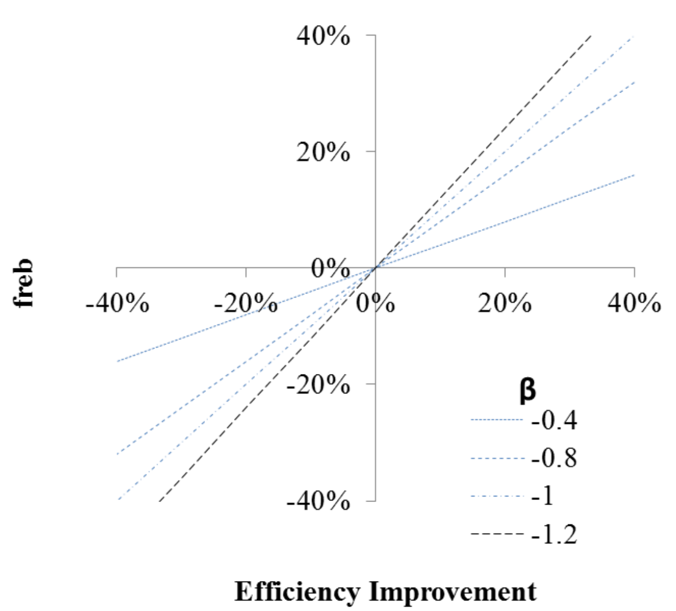

Figure 3.1 Rebound effect (f_{reb}) as a function of change in efficiency and fuel price elasticity (β)

A summary of fuelwood price and income elasticities from the literature is provided in Table 3.3. Elasticity is a measure of the responsiveness of one variable to changes in another, such that inelastic variables (<|1|) are those with changes proportionally less than the other variable, and elastic variables (>|1|) change proportionally more. The sign indicates whether the change represents an increase or decrease. For example, a fuel price elasticity of -0.28 indicates that a 1% increase in price results in a 0.28% decrease in fuel consumption. So the rebound effect for a β of -0.28 paired with a reduction in demand through improved fuel efficiency generates a decrease in price (or time required) and therefore an increase in consumption (Dufournaund, Quinn, and Harrington, 1994). Econometric models of rebound can be developed that incorporate increasing levels of detail and indirect effects, including effects of changes to income and community-wide shifts in spending patterns.

Table 3.3 Income and Fuel Price Elasticities

	α, income elasticity	β, price elasticity	Notes
Zein-Elabdin, 1997	0.87	-0.55	Charcoal, Khartoum
Kidane, 1991[a]	-0.25	-0.37	Fuelwood, Ethiopia
Whitney, 1985[a]	-0.59		Charcoal, Sudan
Hughes-Cromwick, 1985[a]	-0.23		Charcoal, Kenya
Fernandez, 1980[a]	0.51		Non-commercial fuels, Sudan
Egeru, 2010	-3.104	-1.77	Fuelwood, Uganda
Cuthbert, 98 Model 1	0.39	-0.28	Fuelwood, 18 Sub-Saharan African countries
Cuthbert, 98 Model 2	0.4	-0.17	Fuelwood, 18 Sub-Saharan African countries
Cuthbert, 98 Model 3	0.09	-0.08	Fuelwood, 18 Sub-Saharan African countries
Cuthbert, 98 Model 4	0.26	-0.15	Fuelwood, 18 Sub-Saharan African countries
Dunkerley, 1990[b]	-0.7		Fuelwood, India
Macauley, 1989[b]	<0		Fuelwood, India
Pachauri, 1983[b]	0.92	-0.93	Modern & traditional fuels; Urban India
Pachauri, 1983[b]	0.76	-1.15	Modern & traditional fuels; Rural India
Zeinelabdin, 1993[b]	0.86	<0	Charcoal, 20 Sub-Saharan African countries
Leach, 1988	0.32		Rural Sri Lanka
Leach, 1988	0.43		Rural India
Leach, 1988	0.46		Rural Pakistan
Leach, 1988	0.51		Rural Bangladesh
Ekholm, 2010		-0.1 to -0.7	NSSO data for different fuels
Arthur, 2012	0.39	-0.35	Firewood, Rural Mozambique
Arthur, 2012	0.26	-0.23	Charcoal, Rural Mozambique
Arthur, 2012	0.93	-0.78	Candles, Rural Mozambique
Arthur, 2012	0.78	-0.75	Kerosene, Rural Mozambique
Arthur, 2012	0.68	-0.49	Electricity, Rural Mozambique

[a]In Zein-Elabdin, 1997, [b]In Cuthbert, 1998

3.4.6 Life cycle analysis

Life cycle analyses (LCA) consider the energy and emissions required to extract, manufacture/convert, transport/distribute, use, and dispose of products. There are existing software packages that quantify these but have seen limited use in rural energy modeling. The ReCiPe software described in Goedkoop et al. (2008) reports the life cycle by converting the emissions into a measure of direct and embodied impact in terms of a method-specific indicator. It was used by Banerjee and Tierney (2011) to analyze the exergy and environmental impacts of ten different energy systems, including the use of jatropha oil, solar PV, and diesel for electricity generation and solar thermal, biogas, and biomass for thermal applications. Five different methodologies were compared. These are (1) a combination of exergetic analysis with the ReCiPe indicator for emissions; (2) waste exergy to account for extraction and emissions of materials; (3) thermo-ecological costs, which assigns costs to materials; (4) extended exergy accounting, which assigns exergetic values to costs, labor and emissions; (5) and extended thermoeconomics, which converts emissions into costs. A second LCA software package is the Global Emissions Model for Integrated Systems (GEMIS) model. This is an open-source, continuously updated, but currently limited LCA software package that includes environmental, cost, and employment analyses for energy, materials, and transport (IINAS, 2014). Gaul (2013) completed a GEMIS-based life cycle analysis of jatropha fuel in comparison to baseline and other renewable energy options (such as improved or solar cookstoves) for cooking, lighting, and mechanical power for technical and economic viability with sensitivity analysis. Results showed the impacts to be tightly coupled with the production and processing pathways, weak performance for lighting and cooking, and mechanical power dependent upon processing intensity. He concluded that jatropha oil produced and consumed at the village scale to provide electricity represents the best potential use for jatropha oil.

3.4.7 Energy choice and consumption

There are dozens of studies that use regression, logit, and probit-type models to predict the choice and consumption levels of fuel in rural households based on surveys of regional and socioeconomic factors (Chaudhuri and Pfaff, 2003; Farsi, Filippini and Pahcauri, 2007; Heltberg 2004 and 2005; Sapkota and Oden, 2008). Several researchers have performed systematic reviews of this type of study to identify common trends in determinants of energy consumption. Lewis and Pattanayak (2012) used vote-counting meta-analysis in a systematic review that compared 7-13 factors leading to adoption of clean fuels and technologies presented in the literature; finding a positive association with income, education, and urban location for clean fuels and technology; and an unclear influence of fuel availability and price, household size, and gender. They also note that “potentially important drivers, such as credit, supply-chain strengthening, and social marketing have been ignored.” Puzzolo et al. (2013) also performed a systematic review of qualitative and quantitative case studies of improved cookstoves and four clean fuels in terms of seven domains of adoption factors.

3.5 Gaps in the Literature

Although these modeling efforts have contributed to understanding the village energy system, several authors have identified the shortcomings and limitations of the models. Urban, Benders and Moll (2007) and Van Ruijven et al. (2008) assessed whether existing models are suitable for the developing world context, and they identified shortcomings due to fundamental differences relative to the developed world. These differences include the informal economy, the inability of electrification to address needs, the use of traditional bio-fuels, the transition to modern fuels, income distributions, and the urban–rural divide. They argue these differences render present day models incomplete, yet they note that a universal model is unrealistic. Similarly, Henao et al. (2012) asserted that although decision tools have been critical for the design of electrification schemes, their applicability is limited. These limitations include the geographical scale, the participation of the community in decision-making, the narrow number of sustainability dimensions encompassed, the lack of replicability, the lack of measurement of overall impact on peoples' livelihoods, and the lack of consideration of the potential negative impacts or financial drain of improperly selected technologies.

To summarize, existing modeling efforts do not adequately address a number of issues that are needed for the selection of energy technologies for a given village. These include

- A variety of specific devices and fuels with measured performance levels and inclusion of options for changes in energy use practice
- Surveys of actual energy use and load profiles in real rural settings (Howells et al., 2005), with specific tracking of end uses including specialized tasks and the suitability of various devices for each task
- The multi-functional and task-based nature of thermal devices for cooking, water heating, space heating, and specialized cooking processes (Howells et al., 2005)
- Fuel and device stacking with incomplete displacement of traditional technology and over-estimation of impacts (Masera, Saatkamp, and Kammen, 2000)
- Electricity, which is not suited or affordable for thermal tasks even when available
- The rebound effect

- Informal economies and the true pricing and opportunity costs of non-commercial fuels (Van Ruijven et al., 2008; Urban, Benders and Moll, 2007, Ekholm et al., 2010)
- Heterogeneity of household income (Ekholm et al., 2010)
- Indicators of long-term sustainability of projects (Henao et al., 2012)
- Participation of the rural community in decision-making (Henao et al., 2012; Polatdis and Haralambopoulos, 2004).
- Considerations of impacts on rural livelihoods (Henao et al., 2012).
- Quantification of potential negative effects or financial drain (Henao et al., 2012).
- Analysis at the village scale rather than household or regional levels.
- Inclusion of the costs of implementation.
- Strategies targeted based on income or socioeconomic factors.
- Analysis separated by private (household) versus public (social) costs and benefits (Jeuland and Pattanayak, 2012).

Therefore, development of a comprehensive, multi-actor, multi-objective model allowing for investigation of the array of fuels, specific technologies, and changes in practice targeted at individual end uses in the household while incorporating the above missing components is needed for a comprehensive analysis of potential strategies. The goal of such a model would be to allow for the simulation of technological components introduced into the village energy system and analysis of the expected outcomes. In this way the relative impacts, trade-offs, uncertainties, and critical factors for a variety of technologies can be assessed in order to understand the optimal conditions and strategies to provide improved energy services in a given community.

CHAPTER 4

THE INTEGRATED MODEL

In this chapter, an integrated model focused on understanding the outcomes of various village energy service strategies is developed. The intended use of this model is to enable designers and implementers of village energy service strategies to make their decisions based on a holistic understanding of the expected outcomes of a chosen strategy within a village. As shown in Figure 4.1, in the approach presented here, a potential strategy is specified by the designer and applied to the model. This strategy specifies a technological component for each energy service and the fraction of the village expected to adopt it. Data and constraints specific to the community are assessed by the model in order to determine the expected outcomes by considering not only the technology, but the role and behavior of that technology within the system of user needs, constraints, adoption, and behaviors. This interaction of the technology within the system then defines the outcomes of interest from the global to the personal level, including impacts to climate and health, access to energy, economic considerations, and the quality of life offered to the user. These outcomes are then assessed by the designer for a number of strategies and used to make decisions regarding the best strategy to pursue given the objectives and goals of both the implementers and community.

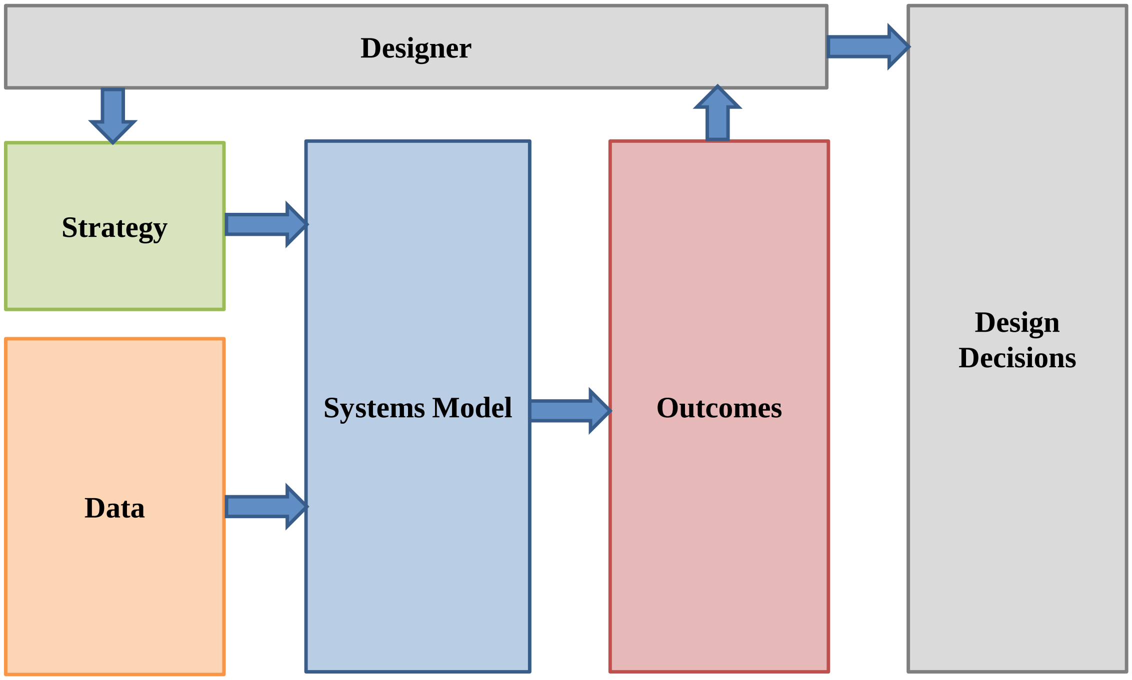

Figure 4.1 Energy system design framework

Figure 4.2 presents a systems diagram of a closer view of the village energy system. It shows that the inputs to the system are the characteristics of the technological components applied to the village. The outcomes produced by these technologies are dependent on a number of operational and adoption processes that occur within the system, which dictate how the technology is used (operational) and the level of expected consumer acceptance dictating how much it is used (adoption). The consumer acceptance piece is a function of how the technology conforms to existing practice and/or if it offers such an improvement that it gives consumers a reason to change existing practice.

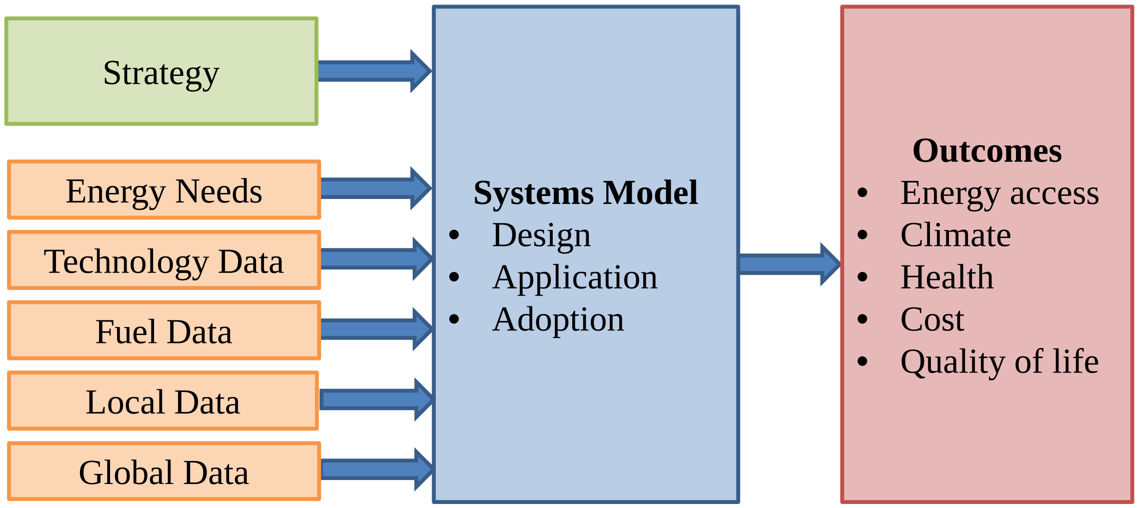

Figure 4.2 The village energy system model

Based on these inputs to, processes within, and outputs from the system, the integrated probabilistic model of the village energy system is developed. The model is initiated by the designer choosing a village energy strategy by assigning a technology to each energy need and an expected level of displacement for each technology. It incorporates input databases of energy needs for various sectors and services in the village, current and potential technological components, local fuels available, and local demographic factors. The model applies the operational and adoption factors numerically through a series of sub-models. It then quantifies the outcomes of the application of the technology in terms of a number of metrics within major objectives describing (1) energy access and efficiency for the needed end uses in the village, (2) environmental impacts, (3) health impacts, (4) economic considerations, and (5) social desirability, disruption, convenience, and safety.

This research is conducted primarily in the context of a rural village in the sahelian region of Africa within the Republic of Mali, a country which ranks 176th out of 187 in the human development index (HDI), has a literacy rate of 33%, and where over half of the population lives below the international poverty line of $1.25 per day (CIA Factbook, 2015). This village was well characterized through routine visits and data gathering by students and researchers from Iowa State University who installed and monitored energy technologies such as biomass cookstoves and community solar battery charging stations from 2006 until a civil war limited access to the village in 2011 (Johnson and Bryden, 2012a and 2012b). Data gleaned from these visits is incorporated into the understanding of village energy needs and systems.

4.1 Databases

The global and local inputs to the model come in the form of five databases called by the model. Community-specific inputs are included in four databases: (1) the annual magnitude of each energy use and indoor or outdoor presence; (2) technology performance expected in the village including efficiency, emissions, economic, lifespan, and social acceptance metrics; (3) fuels including the local lower heating value, cost to purchase, collection time, and harvest nonrenewability factors; and (4) local variables such as labor rate, shadow value, population, and number of cooks. In addition, there is a global database of constants such as global warming potential and indoor air quality guidelines.

4.1.1 Energy Needs

Due to the variety of needs for energy services in a village and the range of technologies that may or may not be suited to each of those services, disaggregated catalogs of annual energy uses are needed for accurate assessments of technology impact. Table 4.1 shows such measures available from the literature, including the Sahelian Malian village (Johnson and Bryden, 2012a), a set of mountainous villages in Southwestern Cambodia (San et al., 2012), and six villages in the dry belt of Karnataka state in India (Astra and Reddy, 1981). Specialized cooking tasks were not disaggregated in the India villages; however, consumption was segregated by fuel type, including fuelwood, rice husk, dung, and kerosene. The variation of fractions of domestic energy use between communities indicates that the optimal cookstove designs or energy strategies to meet major needs will differ between these cultures and communities. Other studies which may provide useful disaggregated annual energy use data include Devi et al. (2009), Kumar and Sharma (2009), Rosas-Floresand Galvez (2010), and Wang and Zhenming (1996).

The Malian village, the primary focus of this research, has the greatest level of detail in energy needs available. In this village, these needs were measured over numerous seasonal visits to the village. The general cooking category includes typical boiling and frying processes conducted primarily on a three-stone fire. The specialized procedures including roasting nuts, rendering oil, making medicine, and steeping tea are also completed on the three-stone fire with the exception of tea steeping, which is done on a small traditional metal stove using charcoal saved from cooking fires. At the time of the measurements, some improved cookstoves had been provided by the researchers and were in use; however, the tasks to which they were applied and the displacement fractions were unclear, and their impact was not statistically significant on overall energy use; therefore, the baseline is assumed to be the three-stone fire here. Heating water for bathing and washing is typically done outdoors on a large fire. Space heating is needed on a seasonal basis for the elderly, often overnight when tending of the fire is minimal. Lighting was provided by kerosene wick lanterns and portable flashlights. Over the course of the village energy survey, researchers worked to install a lighting system including linear fluorescent bulbs powered by lead-acid batteries charged at a centralized station in the community. This solar

Table 4.1 Disaggregated energy consmuption (GJ/y) by end use and sector in several communities

Energy Consumption	Mali[a]	Cambodia[b]	India[c]						
			Arjunahalli	Hanchipura	Keelara	Pura	Sugganahall	Ungra	Average
DOMESTIC									
Cooking	2,230	20,742 ± 438	4,211	3,918	8,855	2,638	3,243	6,034	4,816
Specialized Cooking									
Peanut roasting	106								
Tea steeping	49								
Shea processing	117								
Medicine Making	56								
Animal Feeding		4,572 ± 223							
Animal Protection		9,469 ± 186							
Water heating	947	8,836 ± 345	843	785	2,435	650	589	1,555	1,143
Space heating	814								
Lighting	34		135	117	264	84	122	236	160
ARTISINAL/INDUSTRY	236		428	46	387	170	74	1,213	386
PUBLIC	13								
TRANSPORT	137		24	25	55	17	27	52	33
AGRICULTURE			227	321	414	198	191	471	304
Total	4,739	43,618	5,640	4,890	11,996	3,559	4,055	9,089	6,538
Population	770	4,119	474	424	946	353	446	809	575
Total energy per capita	6.2	10.6	11.9	11.5	12.7	10.1	9.1	11.2	11.1

a Johnson and Bryden, 2012a; b San et al., 2012; c Astra and Reddy, 1981
± is reported standard error, available from San et al., 2012

lighting displaced half of the kerosene usage in the village (Johnson and Bryden, 2012a). In the analysis, it is assumed the lighting system had not yet been installed, and therefore the half of the kerosene reportedly displaced by the introduction of the solar system was added back into the energy inventory. The energy service database includes the number of the service, the name, the energy use in MJ, whether the service is conducted indoors or out, and the default device with which it is conducted in the baseline scenario.

Table 4.2 Performance of Technologies -- Thermal Efficiency (%) and Emission Factors (EF) (g/MJ) with pooled standard deviation from the literature

	Therm. Eff.	$EFCO_2$	$EFCH_4$	EFN_2O	EFCO	EFNMHC	EFBC	EFOC	EFPM	Source	N
Traditional Methods											
Three Stone Fire	0.16 ± 0.02	101.9 ± 11.5	0.24 ± 0.12	0.012 ± 0.009	5.16 ± 1.34	0.458 ± 0.332	0.073 ± 0.036	0.169 ± 0.072	0.319 ± 0.091	a-q	444
Charcoal Tea Stove	0.24 ± 0.08	100.0 ± 8.1	0.49 ± 0.09	0.006 ± 0.000	9.36 ± 1.85	0.514 ± 0.141	0.037 ± N/D	0.097 ± N/D	0.072 ± 0.040	a-c,e-g,k,m,o-q,t	109
Heating Fire	-- ± --	100.0 ± N/D	0.47 ± N/D	0.000 ± N/D	8.78 ± N/D	0.000 ± N/D	0.000 ± N/D	0.000 ± N/D	1.419 ± N/D	x	
Kerosene Lantern	-- ± --	71.9 ± 0.0	0.01 ± 0.00	0.001 ± 0.000	0.40 ± 0.04	N/D ± N/D	2.334 ± 3.083	0.082 ± 0.085	2.459 ± 0.505	u,v,ac	57
Potential Interventions											
Improved	0.28 ± 0.08	97.7 ± 8.5	0.20 ± 0.10	0.016 ± 0.008	2.85 ± 1.23	0.533 ± 0.526	0.089 ± 0.041	0.124 ± 0.018	0.154 ± 0.048	c,d,g,h,k,l,m,o,q,r	142
Advanced	0.45 ± 0.11	101.9 ± 0.0	*0.16* ± N/D	*0.009* ± N/D	3.60 ± N/D	*0.319* ± N/D	*0.004* ± N/D	*0.010* ± N/D	0.018 ± N/D	s	
Gasifier	0.28 ± 0.11	99.1 ± 5.28	0.11 ± 0.05	0.00 ± N/D	1.86 ± 0.41	0.40 ± 0.21	0.01 ± 0.01	0.02 ± 0.02	0.08 ± 0.05	k,m.o,q	22
Forced Draft	0.33 ± 0.07	109.7 ± 6.05	0.02 ± 0.03	0.00 ± N/D	0.57 ± 0.22	0.14 ± 0.08	0.00 ± 0.00	0.01 ± 0.00	0.02 ± 0.03	k,m.o,q	38
Chimney	0.17 ± 0.06	104.2 ± 7.4	0.20 ± 0.11	0.017 ± 0.000	3.30 ± 1.24	0.290 ± 0.267	0.079 ± 0.038	0.080 ± 0.049	0.185 ± 0.097	c,m,j,l,n-q,r,w	213
Communal	0.68 ± 0.17	94.6 ± N/D	N/D ± N/D	N/D ± N/D	1.29 ± N/D	N/D ± N/D	N/D ± N/D	N/D ± N/D	0.034 ± N/D	m	3
Charcoal Stove	0.24 ± 0.08	100.0 ± 8.1	0.49 ± 0.09	0.006 ± 0.000	9.36 ± 1.85	0.514 ± 0.141	0.037 ± N/D	0.097 ± N/D	0.072 ± 0.040	a-c,e-g,k,m,o-q,t	109
Charcoal Production	-- ± 0.00	-- ± 37.5	1.87 ± 1.07	0.005 ± 0.003	13.56 ± 5.20	6.498 ± 6.359	0.001 ± 0.001	0.050 ± 0.049	0.472 ± 0.389	b,e,p,v,aa,ab	23
LPG	0.51 ± 0.04	66.9 ± 2.9	0.00 ± 0.01	0.002 ± 0.000	0.29 ± 0.11	0.299 ± 0.183	0.002 ± 0.002	0.001 ± 0.001	0.008 ± 0.010	c,h,i,m,o,r,t,u,v	27
Biogas	0.57 ± 0.14	69.8 ± 1.4	0.04 ± 0.08	0.017 ± 0.000	0.11 ± 0.05	0.032 ± 0.032	N/D ± N/D	N/D ± N/D	0.030 ± 0.037	c,x	7
Water Preheating	*0.21 ± 0.03*	*101.9 ± 11.5*	*0.24 ± 0.12*	*0.012 ± 0.009*	*5.16 ± 1.34*	*0.458 ± 0.332*	*0.073 ± 0.036*	*0.169 ± 0.072*	*0.319 ± 0.091*	y	
Burning Embers	*0.18 ± 0.02*	*101.9 ± 11.5*	*0.24 ± 0.12*	*0.012 ± 0.009*	*5.16 ± 1.34*	*0.458 ± 0.332*	*0.073 ± 0.036*	*0.169 ± 0.072*	*0.319 ± 0.091*	z	

Italic denotes estimates relative to the three stone fire

a Brocard et al., 1996; b Brocard, Lacaux and Eva, 1998; c Smith et al., 2000; d Venkatamaran and Uma Mashwera Rao, 2001; e Bertschi et al., 2003, f Ludwig et al., 2003; g Bailis, Ezzatti, and Kammen, 2003; i Venkatamaran et al., 2005;j Johnson et al., 2008; k MacCarty et al., 2008; l Roden et al., 2009; m MacCarty, Still and Ogle, 2010; n Christian et al., 2010; o Grieshop, Marshall, and Kandlikar, 2011; p Akagi et al., 2011; q Jetter et al., 2012; r Zhang et al., 2000; s ISO, 2012; t Smith et al., 1993; u Bond et al., 2004; v Forester et al., 2007; w Li et al., 2007; x Bhattacharya, 2000; y Andreatta, 2014; z Johnson and Bryden, 2012a, aa Pennise et al., 2001, ab Lacaux et al., 1994, ac Lam et al., 2012

4.1.2 Technological options

Technical efficiency and emissions performance data for these baseline and potential technologies described in Chapter 2 were collected and compiled from empirical studies in the literature (Table 4.2). Although location-specific empirical field performance data is preferred to laboratory data when available due to the variability of performance between locations, no field data specific to the Malian village is available at this time. This is acceptable since the goal of the present research is to compare broad strategies rather than specific manufacturers or designs.

Thermal efficiency is reported as energy delivered to the cooking pot relative to primary energy consumed, and emission factors are reported as mg pollutant per MJ of energy consumed for CO_2, CO, N_2O, CH_4, black carbon (BC), organic carbon (OC) and particulate matter (PM). These studies represented 444 total laboratory and field data points for the three-stone fire, 142 for the improved cookstove, 3 for the community cookstove, and 27 for LPG cookstove strategies. The advanced cookstove performance was set according to the IWA standard and estimated relative to the three-stone fire for emissions other than CO and PM according to the relative levels of gaseous and particulate emissions in the working agreement (ISO, 2012). The solar water heater and lighting system were assumed to have no emissions. Traditional heating fire emissions were taken from one article (Bhattacharya, Abdul Salam, and Sharma, 2000). Emission factors for traditional tea steeping with charcoal saved from cooking was taken from 109 data points for various types of charcoal stoves. Each study reported results of selected efficiency and emissions metrics. These were pooled based on the number of data points available for each metric, with standard deviations shown in Table 4.2 ranging from 4% to 122% of the mean with an average of 35%. In cases where no data was available, those values were assumed to be zero, or in some cases the standard deviation was estimated as 25% of the mean.

Table 4.3 Technology cost and social factors

	Useful life y	Purchase Cost $US	Maintenance Cost $US/y	Desirability	Disruption	Convenience	Safety	Source
Traditional								
Three Stone Fire			$ -	5	5	5	5	
Charcoal Tea Stove			$ 1	5	5	5	5	
Heating Fire			$ -	5	5	5	5	
Kerosene Lantern			$ 2	5	5	5	5	
Newly Introduced								
Improved	2	$ 15	$ 1	6	3	3	6	a,b,c
Advanced	2	$ 40	$ 4	8	3	2	8	c
Gasifier	2	$ 15	$ 1	5	5	5	5	
Forced Draft	2	$ 40	$ 4	5	5	5	5	
Chimney	5	$ 40	$ 2	5	5	5	5	c
Communal	10	$ 1,000	$ 50	1	1	8	9	
Charcoal	5	$ 15	$ 1	6	5	6	5	
Biogas	30	$ 275	$ 10	5	5	5	5	g,h
LPG	10	$ 60	$ -	10	7	9	7	c,d,i,j
Water Preheating	3	$ 2	$ -	6	4	6	6	
Burning Embers	100	$ -	$ -	5	5	5	5	
Solar Water Heater	15	$ 337	$ 5	10	10	10	10	e
Solar Lighting System	25	$ 15	$ 36	9	10	9	10	f

a Ezzati, Saleh, and Kammen, 2000; b Bailis, Ezzati, and Kamen, 2003; c Still et al., 2011; d Hutton, Rehfuess, and Tediosi, 2007; e Johnson, 2012; f Sloan, Bryden, and McCorkle, 2012; g Chen et al., 2010; h Rajendran, Aslandzadeh, and Taherzadeh, 2012; i Heltberg, Arndt, and Sekhar, 2005; j Kojima, Bacon, and Zhou, 2011

Not every data point included measures of every metric, particularly the emission factors of climate-related emissions, so data for those metrics are sparser.

Financial and qualitative social metrics for the array of selected devices (Table 4.3) were collected from the literature or estimated by the author based on field experience. For devices already existing in the baseline scenario, such as tea stoves and kerosene lanterns, it is assumed there is no cost to purchase associated with these existing devices; however, maintenance cost is included. Social metrics are estimated with baseline devices set at 5 to represent the status quo, and values for other technologies are estimated based on the author's experience. These ratings are critical as they intend to capture the inclination of users to appreciate and therefore adopt or reject a technology. As a result, the categories, weightings, and ratings should be developed directly with the users. The technology database also denotes the fuel it consumes and whether or not it is equipped with a chimney.

4.1.3 Fuels

A menu of potential fuels and their associated costs, collection times, and harvest renewability levels in the community is also needed (Table 4.4). The cost of fuel is accounted for by both the market value and the associated opportunity cost of time modeled as lost income. Fuelwood is freely collected by women and children, requiring an average of 40,000 hours per year for an equivalent of 9.4 hr/GJ at the 14.8 MJ/kg lower heating value measured in the village (Johnson and Bryden, 2012a). The fuel cost for wood is assumed as zero in this case; however, in places where a fuel market exists, the lost income due to consumption rather than sale may also be taken as an opportunity cost. The cost of LPG is assumed to be $25/GJ (World Bank, 2001) with an LHV of 46 MJ/kg given by BHARAT petroleum Corp. Ltd. (Smith et al., 2000). It is assumed the default labor rate in this village is $2/day with a shadow value of time of 50% used to account for the potential lack of paid employment opportunities even if the time is available for working (Jeuland and Pattanayak, 2012). It is also assumed the user discount rate is 50%, per an income-based review presented by Ekholm (2012). For climate calculations, the fuel harvest nonrenewability factor (f_{NRB}) is taken as 0.73 for wood (CDM, 2014) and 1.0 for LPG. For calculations of rebound, the fuel price elasticity for fuelwood is taken as -0.28 from Table 3.3 (Cuthbert and Dufournaud, 1998) and zero for LPG. Though present in the model for future work, implementation cost and life cycle analyses are omitted in this study due to a lack of authentic input data at this time.

Table 4.4 Fuels

Name	LHV (MJ/kg)	Cost ($US/GJ)	Time (hr/GJ)	fNRB	Beta
Wood	14.8 [a]	0	9.3 [a]	0.73 [b]	-0.28 [c]
Saved Charcoal	29.7 [a]	0	0	0.73 [b]	-0.28 [c]
Kerosene	43.3 [d]	25 [e]	0	1	0
LPG	46 [d]	25 [e]	0	1	0
Biogas	18 [f]	0	4.7	0	0
Solar		0	0	0	0
Diesel	45 [a]	26	0	1	0
Gasoline	43.5 [a]	31	0	1	0
Commercial Charcoal	28.5 [a]	2 [h]	0.0	0.73 [b]	-0.55 [g]
Disposable Battery	0.616	20000 [h]	0	1	0
Prepared Biomass	14.8 [a]	0	9.3 [a]	0.73 [b]	-0.28 [c]

a Johnson and Bryden, 2012a; b CDM, 2010; c Cuthbert and Dufournaud, 1998; d Grieshop, Marshall, and Kandlikar, 2011; e World Bank, 2001; f Smith et al., 2000;g Zein-Elabdin, 1997; h estimated

The cost of purchased made charcoal is assumed to be 1/10th the cost of LPG for lack of better data. Prepared biomass is assumed to be collected biomass prepared into smaller pieces such as pellets or briquettes as needed for specialized cookstoves such as gasifiers. These are assumed to require 10% more time for processing in addition to the time for collection.

4.1.4 Local variables

In addition to the local price and renewability levels of fuels, additional community variables are needed. Table 4.5 shows the needed local demographic and geographic variables. The Malian village consists of 770 people, encompassing 60 families with 123 women cooking regularly and 129 heating fires in operation seasonally (Johnson and Bryden, 2012b). Of the 123 cooks, 76 use their own stove and 21 share a kitchen with another cook, for a total of 97 cookstoves needed to supply the entire village (Johnson, 2012). At 100% displacement, it is assumed that 97 cookstoves are needed for the improved, advanced, and LPG scenarios. For the solar water heater calculations, it is assumed each person requires 10 L/day of hot water and the full 100-L volume of the water heaters shared across the community are used once per day (Johnson, 2012), and for communal cooking it is estimated that each person requires 1 L/meal of prepared food. The number of devices required is then subject to the displacement fraction.

Table 4.5 Local variables

Demographic	Economic
Population	Income
Number of families	Subsidy
Number of cooks	Discount rate
Number of heating fires	Labor cost
Liters hot water per person	Shadow fraction
Heating fraction of cooking	
Hours lighting from cooking	

It is assumed the average labor rate in the village is that of unskilled labor, or $2 per day. The effective discount rate at this level of income is assumed to be 50% based on the research of Eckholm et al. (2010). The shadow fraction of time, or the fraction of free time that would be available for paid work opportunities, is roughly estimated to be 50% (Jeuland and Pattanayak, 2012).

4.1.5 Global variables

In addition to the variables that change in relation to the community, there are global variables that do not. These global constants include the global warming potentials listed in Table 3.2, the WHO indoor air quality guidelines, and weighting of metrics as needed.

4.2 Sub-models

As shown in Figure 4.3, the model operates first by creating the input file, then running the energy needs and technology sub-models, and finally the creation of the output files. The catalog of each energy usage in the village, *i*, is iterated through progressively if selected in the analysis in order to tally all of the energy usages at the village scale. All potential technologies, *j*, that are included in the strategy are also iterated to assign costs and embodied energy and emissions due to the procurement of technologies. In this way the sum of the impacts of each energy need in the village and the costs of each new device introduced are analyzed.

As seen in Table 4.2, the standard deviation measured for some performance metrics can be as high as 122% of the mean, indicating that there can be a great deal of variability in performance measures. To account for uncertainty and variability in all of these input parameters, a probabilistic Monte Carlo analysis is used. In this methodology, each input parameter, *x*, is randomly assigned a normally distributed value according to its measured, reported, or estimated average and deviation. In cases where uncertainty in the input data from the literature was not available, such as the energy use data, standard deviation is assumed to be

25% of the mean. The model is then iterated 1,000 times, reporting average results and uncertainty as 95% confidence interval.

$$x[iteration] = distribution\left(average\left(x\right), deviation\left(x\right)\right) \tag{2}$$

During the first run of the model, the baseline scenario data must be initialized. This is done by running through the model all energy needs assigned to their baseline technologies at 100% displacement. The baseline impacts, $y_{baseline}$, are then initialized and stored for future analyses.

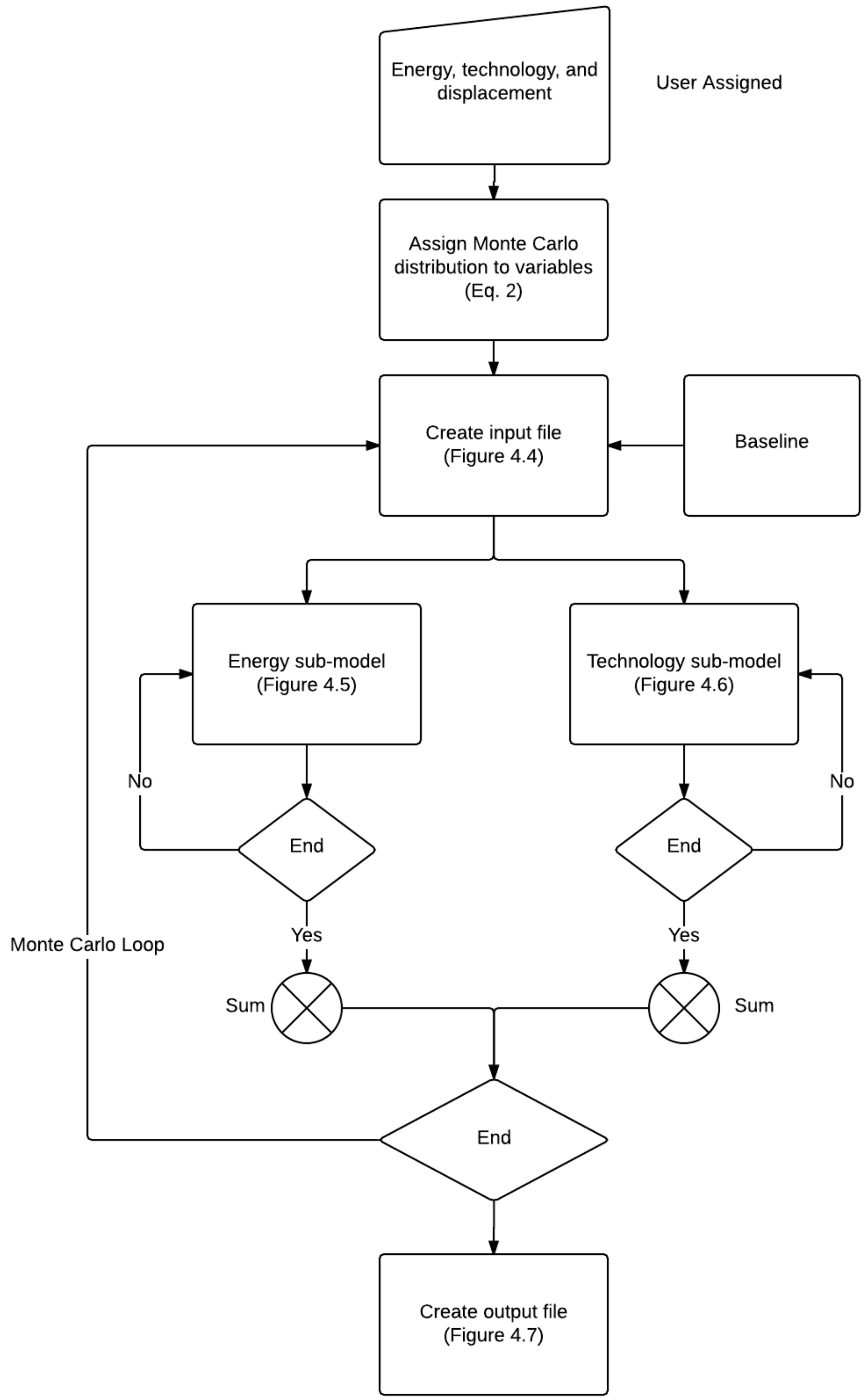

Figure 4.3 Operation of the model

4.2.1 Creation of the input file

Figure 4.4 shows the operations needed to create the input file. This is done by first reading the databases discussed in section 4.1. To run the model, the designer assigns each annual energy end use in a village, *i*, to a specific practice or technology, *j*, which is assigned a specific type of fuel in the database. The technology can either be the default baseline device as indicated in the energy need database or a strategy of interest applied at a defined fraction of the population adopting the new technology to displace the traditional method for each task, $f_{dis,i,j}$. This can be modeled based on socioeconomic factors, utility functions, or diffusion models; assumed as in Limmeechokchai and Chawana (2007), or taken as a model input. At this time it is taken as a model input. These assignments can take place either via a web interface, or in the case of the current model operation, a series of strategies are out in a flat stack and run through progressively.

If the simulation is annotated as the baseline analysis, the displacement fraction is 1 and the model is run initially in order to fill in the set baseline variables. After that initial run, if the displacement fraction of the new technology is less than 1, the fraction remaining undisplaced is included in the impact (*y*) total with the remaining fraction assigned to the baseline values.

$$y_i = f_{dis,i,j} y_i + \left(1 - f_{dis,i,j}\right) y_{base} \tag{3}$$

The three-stone fire provides cooking, lighting, and heating simultaneously, as do some other potential technologies. In the case of multifunctional devices, the multiple types of energy outputs are tracked simultaneously via their cooking, heating, and lighting efficiencies. These are paired with capacity factors representing the fraction or quantity of time that an additional service is desired. If the multifunctional analysis capability is turned on in the analysis, when the

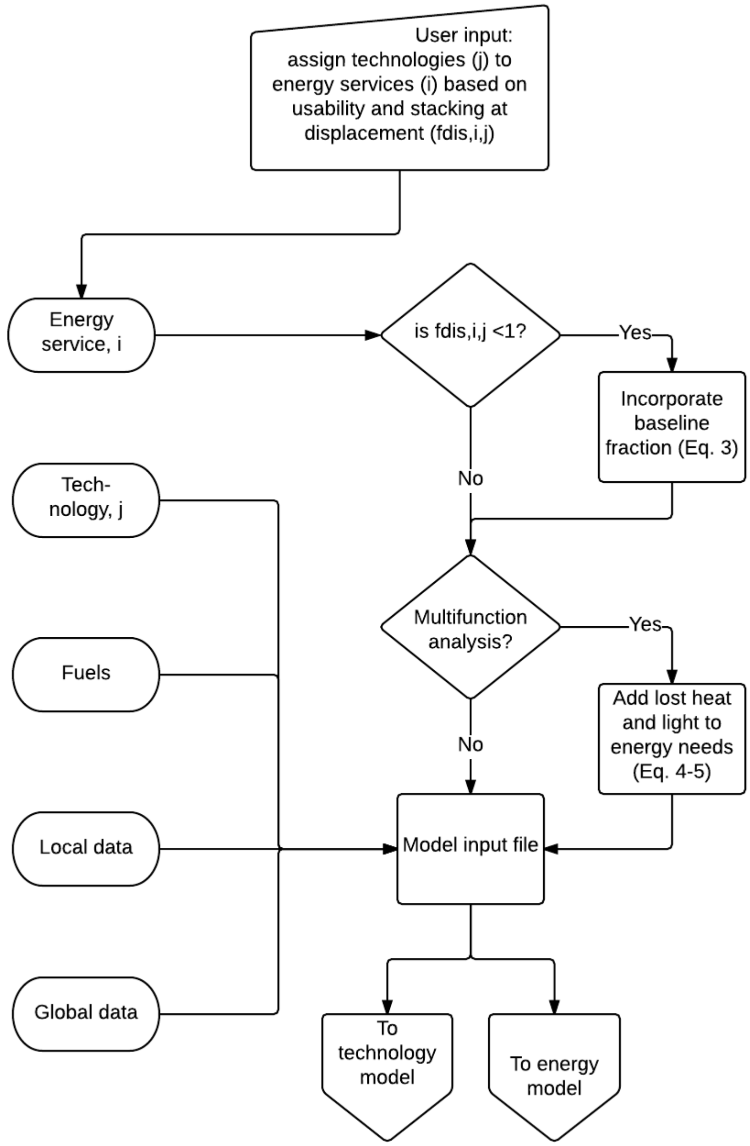

Figure 4.4 Development of the input file

three-stone fire for cooking is displaced, the heating and lighting functions are lost. These lost auxiliary contributions are added to the space heating and lighting requirements in the baseline situation, which must be then made up for by increased use of traditional heating and lighting sources. This occurs in any scenario where the multifunctional nature of tasks is reduced. For example, if an improved cookstove reduces light output below a set threshold relative to the three-stone fire due to view blockage to the flames and reduced luminosity and firepower, the kerosene lantern is used more often to make up for these hours of missing lighting, and the emissions and cost reflect this. Any contributions to lighting and heating of improved devices are accounted for in the same way.

$$AEU_{heating,total} = AEU_{heating,measured} + f_{cap,heating}\left(1-\eta_{TSF}\right)AEU_{cook} \qquad (4)$$

$$AEU_{light,total} = AEU_{light,measured} + 1.314 \cdot N_{TSF} \cdot Q_{kerosene} \qquad (5)$$

The fraction of cooking energy that also provides space heating is determined assuming the cooking process is also appreciated for heat, but only during the latter half of dinnertime cooking (one-sixth of the day), and only in the cool season (one-fourth of the year). This equates to a capacity factor of $f_{cap,heat}$ =0.042. The heating efficiency of the three-stone fire (TSF) is equal to 1 minus the cooking efficiency. For lighting it is assumed each three-stone fire provides 1 hour of useful light per day in the evening during cooking, and therefore the energy required to provide this hour by a kerosene lantern is equal to a product of the hours of lighting average wattage of kerosene lanterns listed in the technology database, $Q_{kersosene}$.

Given this set of energy needs and technologies, the model input file is complete. This information is then sent to iterate through the energy sub-model for each energy need, which calculates the impacts of the energy consumption, and then sent to iterate through the technology sub-model, which calculates the cost and impacts associated with procuring the new devices in the village.

4.2.2 The energy need sub-model

As shown in Figure 4.5, the energy needs sub-model operates by reading the energy needs and their assigned technologies and displacement fractions from the input file and then reporting the impacts of energy use in terms of energy, climate, health, and social metrics. Development of algorithms for these impacts is based on standard equations and methodology collected from the literature. All calculations are then based on first calculating the annual energy consumption for that energy service need assuming the same level of energy service is delivered as was measured in the baseline. The energy consumption is also a function of the rebound effect discussed in Section 3.4.5. The anticipated rebound effect, $f_{reb,j}$, of the new technology is due to the improved efficiency of the change and is related to the fuel price elasticity, β (Eq. 1). Incorporating these factors results in the metrics of annual energy use (*AEU*) for each village energy task, *i*, and device, *j*, in MJ. Equation 6 shows the energy consumption from each new device subject to both the displacement fraction and rebound, and the baseline use subject to the energy that was not displaced.

$$AEU_i = \left(\Delta\eta_{\left(j_{post} - j_{pre}\right)} \cdot \left(-\beta_{fuel} - 1\right) + 1 \right) f_{dis,i,j} AEU_{i,pre} + (1 - f_{dis,i,j}) AEU_{i,pre} \qquad (6)$$

4.2.2.1. Energy

A primary technical objective of energy services is to provide access to useful energy, or the energy delivered to complete a required task such as heating a liter of water or providing a lumen of light. Energy delivered is separated by the type of energy output (thermal, mechanical, and luminous) and is based on the conversion efficiency of the device. In the case of cooking, efficiency is the fraction of energy transferred into the pot $\eta_{cook,j}$, and is determined empirically in the literature. For space heating, efficiency is the fraction of heat delivered into the room, often assumed as 1 minus the cooking efficiency in cases where no chimney is present. Efficiency is in terms of the power at the shaft in the case of mechanical energy (Gaul, 2013).

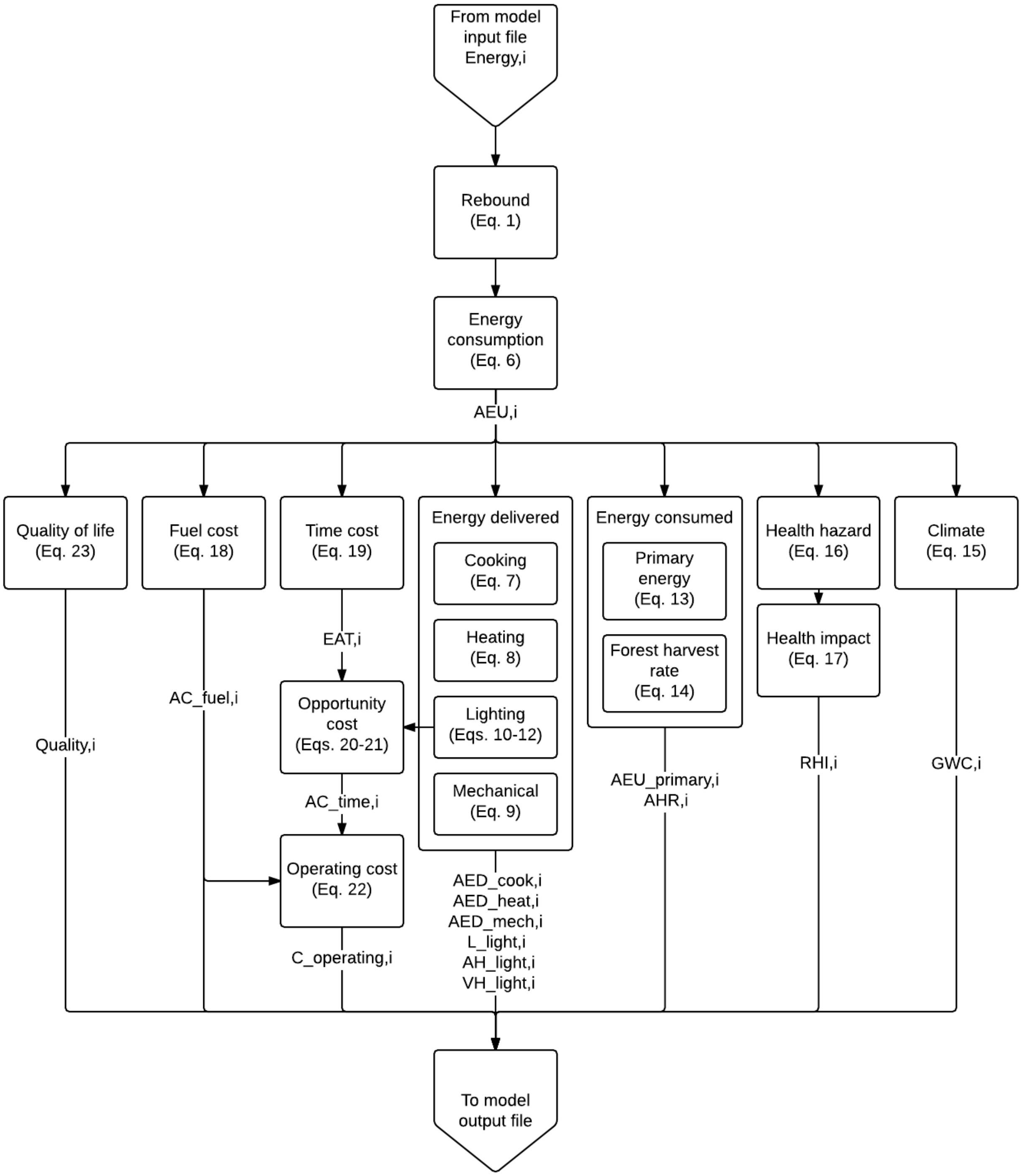

Figure 4.5 The energy need sub-model

$$AED_{cook} = \sum_i \sum_j \eta_{cook,i,j} f_{dis,i,j} AEU_i \tag{7}$$

$$AED_{heating} = \sum_i \sum_j f_{heat,i} \eta_{heating,j} f_{dis,i,j} AEU_i \tag{8}$$

$$AED_{mech} = \sum_i \sum_j \eta_{mech,j} f_{dis,i,j} AEU_i \tag{9}$$

For lighting, energy analysis is more complicated as there are several metrics of interest, including the duration of lighting available (H_{light}), the intensity or lumen output of that light (L_{light}), the resulting lumen-hours, and the quantity of hours of lighting that is of strong enough quality/intensity to conduct educational or productive activities (VH_{light}). As discussed earlier, lighting is measured in terms of effectiveness rather than efficiency by the lumens delivered per watt of energy consumption. The hours made available by lighting systems ($H_{light,i,j}$) are a function of the power and capacity of the system, for example, the volume of kerosene for fuel-based lighting or the battery capacity available on a daily basis from a solar-charged system. The lumen output of that light (L_{light}) is determined from the lighting efficacy, η_{light}, in lumens per watt of each device paired with its firepower. In the village at the baseline scenario, 34 GJ of kerosene is consumed for lighting in kerosene lanterns that operate at an average power of 200 W with a luminous efficacy of 0.04 lumens/W (Mills, 2011). This indicates that approximately H_{light}=47,500 hours of kerosene lighting are provided in the village, or approximately 1-1.5 hours per day per household at an output level of 8 lumens. The linear fluorescent bulbs in the community-charged battery systems are assumed to consume 7 W of power each (Sloan, Bryden, and McCorkle, 2012). The 12 V lead acid batteries are rated at 100 Amphr, or 1200 Whr per battery. It is assumed each family (as measured by the number of cooks) consumes one full battery charge per month at a cost of $3 per charge to operate three 7 W linear fluorescent bulbs at an average luminous efficacy of 75 lumens/W (Sloan, Bryden, and McCorkle, 2012). This equates to 1.9 hours of light per household per day at a level of 1,575 lumens.

$$L_{light,i,j} = \eta_{light,j} Q_j \tag{10}$$

$$AH_{light} = \sum_i \sum_j H_{light,i,j} \tag{11}$$

It is assumed that the lighting efficacy of the three-stone fire is comparable to that of kerosene lanterns, and the kerosene lantern is used after dark when the cooking fire is not operating. However, in the case of cookstoves, most of the useful firelight is blocked by the stove body; consequently, the lighting efficacy is assumed to be zero and the kerosene lantern must be run simultaneously if lighting is needed. When the intensity of light provided by a new device is great enough for activities such as education and productive activities to be conducted, these hours of lighting are valued separately from the low-level light produced by kerosene or firelight. These valued hours (VH_{light}) are tallied when greater than a given intensity threshold, when $L_{threshold}$ > 500 lumens.

$$VH_{light} = \sum_i \sum_j H_{light,i,j} \mid L_{light,i,j} > L_{threshold} \tag{12}$$

An additional objective is to minimize primary energy use, whether from fossil or biomass fuels, in favor of renewable energy such as solar. Primary energy uses include biomass and fossil fuels but excludes solar or biogas fuels. In addition, the forest harvest rate is tracked by monitoring the use of biomass energy to allow for analysis of fuel harvest renewability.

$$AEU_{primary} = \sum_{i,primary} AEU_i \tag{13}$$

$$AHR = \sum_{i,fuelwood} \frac{AEU_i}{LHV_{fuelwood,as-rec'd}} + \sum_{i,charcoal} \frac{\frac{AEU_i}{LHV_{charcoal}}}{\eta_{charproduction}} \tag{14}$$

4.2.2.2 Climate

The annual global warming commitment (*GWC*) of each energy use and device combination is calculated as metric tons of carbon dioxide equivalent (tCO_{2e}) through the summation of the emissions of each product of incomplete combustion (PIC), *k*, weighted by its *GWP* (Table 3.2). The *GWP* are global data that incorporate the relative forcing of a unit of substance relative to CO_2 on a 20 or 100 year timeline. Emission factors, or the mass of greenhouse gas or aerosol emitted per MJ of fuel combusted, available from the technology database for the various fuels and devices are determined empirically in the literature.

$$GWC = \sum_i \sum_j \left(EF_{CO_2,j} \cdot f_{NRB,fuel} \cdot AEU_{i,j} + \sum_k EF_{k,j} \cdot AEU_{i,j} \cdot GWP_k \right) \qquad (15)$$

In the case of charcoal fuel, the emissions produced during production of a MJ of charcoal are added into the warming commitment.

The nonrenewability fraction of the fuel, f_{NRB}, from the fuel database is applied to the carbon dioxide emissions, and it ranges from 0 for fully sustainable biomass harvest to 1 for deforestation or fossil fuels. The CDM executive board lists country-wide biomass default values f_{NRB} (CDM, 2010); however, the differences in renewability between regions exhibits significant granularity based on forest proximity and availability and use of tools for felling trees versus collection of fallen branches.

4.2.2.3 Health

A wide array of health metrics were used in previous studies (Section 3.4.2). Because these models of emissions and exposure were not quite suited to the objectives of this model, the Relative Hazard Index, or the volume of air required to dilute a given mass of emissions to “safe” levels, used by Smith (1994) was selected as the metric of choice. The RHI was chosen because (a) it can be summed at the village scale for various tasks and devices, (b) it does not require measurements of indoor air quality in rural homes, which is highly variable between time, monitoring location, household, and region, (c) it can be computed using device-specific emission factors available in the literature, (d) ventilation factors can be applied, and e) multiple pollutants can be considered simultaneously.

In a typical village, some tasks are completed indoors, some outdoors, and some potentially indoors with chimneys. Therefore, an unvented factor, $f_{unv,i}$, is applied to the emission factor to account for the increased ventilation offered by completing tasks outdoors or with a chimney. For indoor tasks with limited ventilation, this value is equal to 1. To account for the risk difference between indoor and outdoor tasks, the ratio of annual deaths due to outdoor (0.5 million) to indoor (3.5 million) air pollution from cooking and heating as reported by (Lim et al., 2012) is used, or $f_{unv,i}$=0.125. Further, for indoor cookstoves with chimneys, the unvented fraction is taken as 0.18 as determined by Grieshop,Marshall, and Kandlikar, (2011). Use of an active or passive emissions extraction hood within the home or the effect of increased ventilation can also be considered with f_{unv} estimated or determined experimentally (Grabow, Still and Bentson, 2013; Johnson et al., 2011).

The National Ambient Air Quality Standards (NAAQS), or Air Quality Guidelines (AQG) in the equation below are 35 μg/m^3 for the “interim target 1” and 25 μg/m^3 for the “interim target 2” and overall value for $PM_{2.5}$ averaged over 24 hours (WHO, 2006), and 7 mg/m^3 averaged over 24 hours for CO (WHO, 2010). Other emissions, such as those of semi-volatile organic compounds (e.g., formaldehyde and benzo[*a*]pyrene), methylene chloride, and dioxins, are a) not as well characterized from household energy devices and b) are not “criteria” pollutants in the NAAQS and are therefore not considered here. Thus the RHI for each use *i*, device *j*, and species *k*, of interest (CO and PM) is calculated as the volume of air per day required to dilute the emitted mass to the given AQG.

$$RHI_{i,j,k} = \frac{f_{unv,i} EF_{j,k} AEU_{i,j}}{\mathrm{AQG}_k} \cdot \frac{1}{365} \qquad (16)$$

The overall health metric for a given scenario is then calculated as the sum of the hazard index for each energy use by taking the maximum RHI for CO or PM (since sufficient dilution is inherently provided to the lower of the two) .

$$RHI = \sum_i \sum_j MAX\left(RHI_{i,j,\mathrm{PM}}, RHI_{i,j,\mathrm{CO}}\right) \qquad (17)$$

4.2.2.4 Economic

There are two operating costs associated with energy consumption: fuel costs and time costs, which may represent opportunity costs. The annual financial cost of any purchased fuels will be borne by the users in terms of the purchase cost, C_{fuel}, per MJ of energy, discounting any fraction that might be freely collected $f_{coll,fuel}$.

$$AC_{fuel} = \sum_i \sum_j \left(1 - f_{coll,fuel}\right) AEU_{i,j} C_{fuel} \qquad (18)$$

Although locally collected fuelwood may present no direct financial cost, the time and energy spent in these trips accounts for a significant opportunity cost of time and caloric energy. For example, in the Malian village, 40,000 hours per year is spent collecting fuelwood, or an average of C_{time}= 0.00935 h/MJ (107 MJ/h) for wood fuel. The time required for other fuels, such as operating of a biogas digester, can be calculated in a similar fashion. In addition to collection time, each potential device may include a fuel preparation factor, $f_{prep,j}$, equal to the preparation time required relative to the baseline and applied to the fuel collection time. The estimated annual hours (AH_{fuel}) involved with procuring fuel is shown in Eq. 19.

$$AH_{fuel} = \sum_i \sum_j f_{coll,fuel} AEU_{i,j} f_{prep,j} C_{time,fuel} \tag{19}$$

To monetize the time into opportunity cost, the potential labor rate, C_{labor}, is used. Because not all of that time will be used for income generation, the fraction of available time that would have a potential for income generation is represented by the shadow value of time, f_{shadow}.

$$AC_{time} = f_{shadow} C_{labor} AH_{fuel} \tag{20}$$

In the Malian village, it was found that when electric lighting was installed, the quality of light available after sunset gave them the time to weave baskets for sorting grain to be sold at the market in Bamako. This created an opportunity for generating income, such that sometime after installing the lighting system described in Section 4.1.1, when the researchers returned to the village they found that many homes had their thatch roofs replaced with tin due to the newly-available income. Therefore, it is important to include this additional income in the scenario, estimated as a product of the valued hours of light VH_{light}, the shadow value of time and going labor rate.

$$AC_{light} = \sum_i \sum_j f_{shadow} \left(-C_{labor}\right) VH_{light,i,j} \tag{21}$$

Combining all three components of ongoing cost results in the operating cost.

$$AC_{operating} = AC_{fuel} + AC_{time} + AC_{light} \tag{22}$$

4.2.2.5 Social

Regardless of the potential performance of a technology, benefits will not be realized if there is no motivation for adoption or satisfactory operation for sustained use. In this framework, this social metric of quality of life serves as a way to approximate this important component as well as the overall appropriateness of a strategy, and in many ways this social metric can serve as a proxy for anticipated adoption (displacement) fractions. In the future, the categories and valuation system for the characteristics of energy technologies should be developed in close consultation with users in a community. Initially, development of this qualitative metric by the author based on beliefs and field experiences encompasses four areas:

- Desirability–No matter the development stage of their community, consumers seek well-designed, quality devices. Some development programs focus on the “aspirational” nature of their design as a market driver, attempting to ensure a high perceived value and overall worth to the user. This metric also includes aesthetic benefits such as a cleaner kitchen and improved social standing (Jeuland and Pattanayak, 2012).
- Disruption–Tradition, habit, and experience shape human behavior. The alteration of the manner of preparing food is commonly termed behavior change and the understanding of the mechanisms of why and how change happens is complex (Stanistreet et al., 2015). Devices that require a change in the timing, method, or practice of energy use will likely face difficulty, and insensitivity to these is a common downfall of development projects (Slaski and Thurber, 2009).
- Convenience–Convenience in terms of ease of use and amount of attention required is important to consumers. For example, the cook may be away from a cooking fire for up to 15 minutes to tend to other tasks, yet improved cookstoves often require more frequent tending than a heavily stoked open fire (Johnson and Bryden, 2013).
- Safety–Product safety codes are standard operating practice in developed countries and should be a key concern in development projects as well. A safety rating system for cookstoves to address surface temperatures, stability, and containment of combustion is

available (Johnson, 2005). Modern fuels also pose safety risks, such as the toxicity and flammability of ethanol or electrical wiring when not installed to code.

These variables should be quantified based on user feedback and surveys designed with input from social scientists and executed with cultural sensitivity. Loosely based on the analytic hierarchy process methods of Ramanathan and Ganesh (1995), each of the four categories are ranked, *x*, on a scale of 1–10, with 5 representing the baseline situation. An overall quality of life metric is generated with the four areas, *m*, weighted by importance, *w*, equal for each by default.

$$Quality_{i,j} = \sum_{m=1}^{4} w_m \cdot x_{i,j,m} \qquad (23)$$

The average across all tasks is then taken to determine the quality of life offered by the strategy in the village. Analysis currently weights these by energy usage for each task. However, for lighting services, this provides too low of a weight due to the relatively low energy use, so a different weighting system would be beneficial to account for the relatively high importance and value to the users offered by lighting.

4.2.3 The technology sub-model

The technology sub-model is needed to determine the costs and impacts associated with the introduction of a new technology into the village energy system.

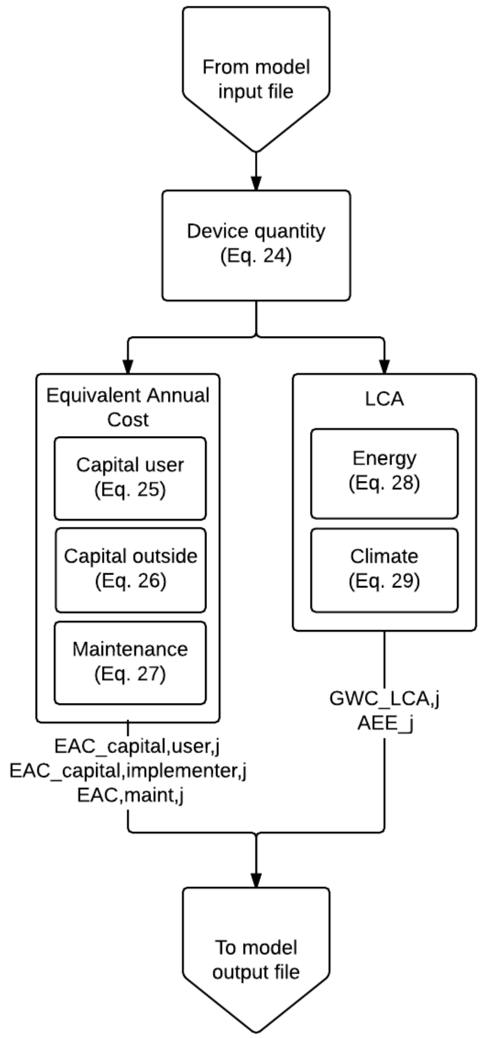

Figure 4.6 The technology sub-model

4.2.3.1Technology capital costs

The introduction of a technology includes capital costs as a function of the number of devices required in the village. These costs are borne by some combination of user funds or financing, donor capital, and government subsidy or tax breaks on imported technologies (Modi et al., 2006). And the benefits of costs are spread out and averaged over the timespan for which the device is in use.

The quantity of each type of device required in the village, N_j, is determined based on (a) the number of cookstoves in the village, which is a function of the number of cooks in the case of cookstoves or lighting systems, (b) the population of the village and consumption per capita factored by the device capacity if a communal device such as a solar water heater or communal cookstove is used, or (c) the measured number of heating fires in the case of a heating stove. This quantity is then subject to the displacement fraction, $f_{dis,i,j}$.

$$N_j = f_{dis,i,j} N_i \tag{24}$$

For devices that must be purchased when not already in use in the baseline scenario, the equivalent annual cost (*EAC*) of a device is dependent on the purchase price, $C_{purchase}$, and useful life, T_{useful}, of that device as well as the discount rate, r. Costs to the user and implementer are tracked separately as a function of the subsidy fraction for the device, $f_{subsidy,j}$. For the implementer, the discount rate is typically taken as 5%. However, if any of the purchase price is borne by the user, the discount rate should be determined from household economic conditions. A regression with income level in India showed a discount rate of 74% in low income rural communities (Ekholm et al., 2010), but Jeuland and Pattanayak (2012) used private discount rates of 10%-20%. In some cases the purchase price may be financed by microfinance organizations, in which case the down payment, interest rates, and amortization terms can also be included in the analysis.

$$EAC_{capital,user} = \sum_j N_j \left(\left(1 - f_{subsidy,j} \right) C_{purchase,j} \right) \frac{r_{user}}{1 - \left(1 + r_{user} \right)^{-T_{useful,j}}} \tag{25}$$

$$EAC_{capital,imp} = \sum_j N_j \left(\left(f_{subsidy,j} \right) C_{purchase,j} \right) \frac{r_{imp}}{1 - \left(1 + r_{imp} \right)^{-T_{useful,j}}} \tag{26}$$

Maintenance of a device is of particular importance to ensure ongoing service, especially in areas where spare parts and technical expertise are limited. The annual maintenance cost of a device, C_{maint}, whether for replacement parts or technician visits, is added to the annual cost to the user.

$$AC_{maint} = \sum_{j} N_j C_{maint,j} \tag{27}$$

4.2.3.2 Technology life-cycle analysis

The energy and emissions embodied in a technology due to manufacture and implementation may also be considered through life cycle analysis (LCA). This includes the embodied energy *(EE)* required to manufacture and transport devices and fuels. The annual embodied energy of a device (*AEE*) is a function of the number of devices and device lifetime ($T_{useful,j}$). This data may be available through LCA software packages such as GEMIS (IINAS, 2014) or Open LCA (OpenLCA, 2014).

$$AEE = \sum_{j} \frac{N_j EE_j}{T_{useful,j}} \tag{28}$$

Emissions generated throughout a product life cycle including extraction, manufacturing, transport, and disposal of various technologies, (GWC_{LCA}) may also be included. These are based on the mass of materials in each device and reported as energy consumed and emissions released per kilogram (*ef*) of material manufactured. These are also available in an LCA database. For such an analysis, the mass, *m*, of each material, *l*, in the finished product, as well as details on the source and distance to the consumer is included.

$$GWC_{LCA} = \sum_{j} N_j \sum_{k} \sum_{l} m_{j,k,l} \cdot ef_{k,l} \cdot GWP_k \tag{29}$$

Although present in the model, data for LCA in the Malian village is not incorporated at this time.

4.2.4 Creation of the output file

Finally, the impacts for each energy need and technology are totaled and passed on to create the output file (Figure 4.7). The programmatic and implementation costs and climate impacts including salaries, travel, community education, etc. can vary widely for projects, scopes, and situations. Examples of these are available in Hutton, Rehfuess, and Tediosi (2007) and Garcia-Frapolli et al. (2010).The totals for energy, climate, and cost contributions from both energy consumption, technology purchase, and implementation are combined.

$$GWC_{total} = \sum_i GWC_i + \sum_j GWC_{LCA,j} + GWC_{implement} \tag{30}$$

$$EAC_{total,user} = AC_{operating} + EAC_{capital,user} + AC_{maint} \tag{31}$$

$$EAC_{total,implementer} = EAC_{capital,implementer} + AC_{implementation} \tag{32}$$

$$EAC_{total} = EAC_{total,user} + EAC_{total,implementer} \tag{33}$$

Costs can then be analyzed in a variety of ways, including the payback time through fuel and time savings and levelized cost of energy (*LCOE*). The average fraction of household income (f_{income}) in the village spent on energy services is determined from the annual fuel and device purchase/maintenance costs for each family with an annual income assumed from one household member employed at the going labor rate for 40 hours per week 4 weeks per month. The fraction of household income spent on energy is an illustrative metric for scenario comparison.

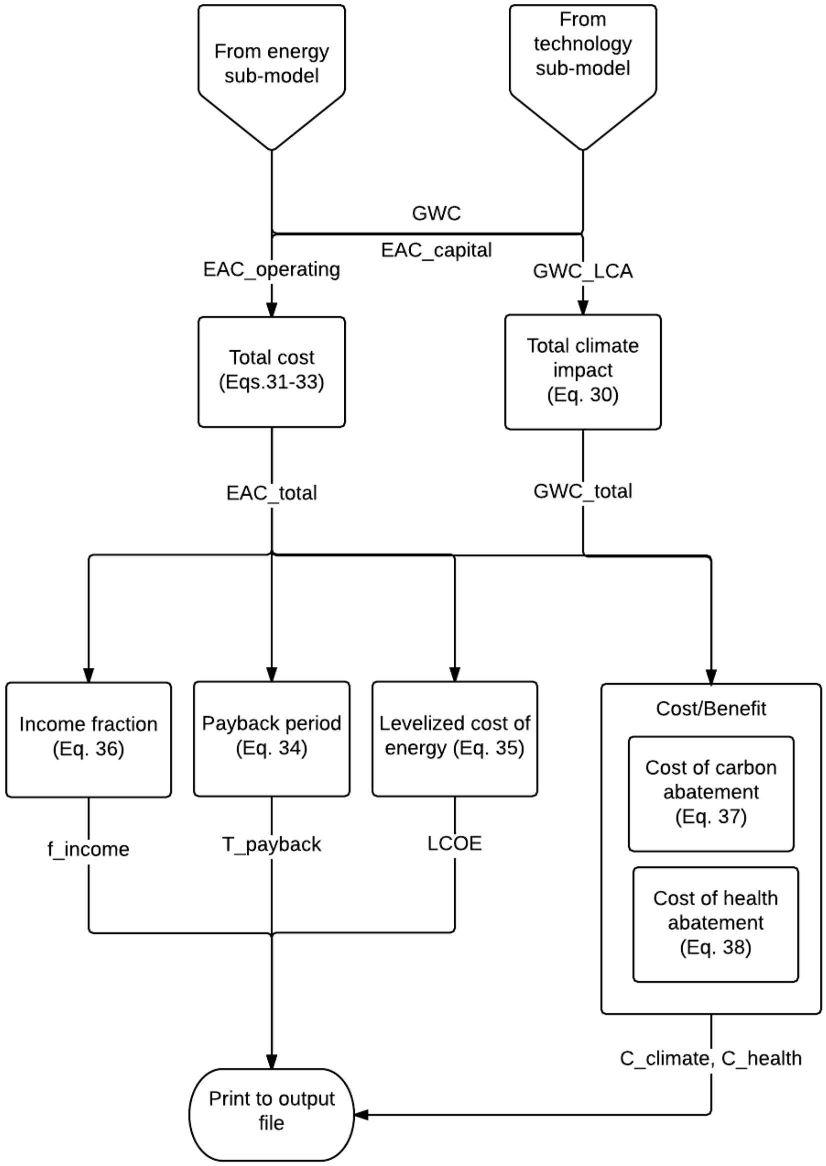

Figure 4.7 Development of the output file

$$T_{payback} = \frac{\sum_j N_j C_{purchase,j}}{\left(EAC_{fuel} + EAC_{time}\right)_{base} - \left(EAC_{fuel} + EAC_{time}\right)_j} \tag{34}$$

$$LCOE = \frac{\sum_{t=1}^{n} \frac{\sum_j \left(N_j C_{purchase,j,t} + N_j C_{maint,j,t}\right) + \sum_i AEU_{i,j}\left(C_{fuel,j,t} + C_{time,fuel,j,t}\right)}{(1+r)^t}}{\sum_{t=1}^{n} \sum_i \frac{AED_{i,j,t}}{(1+r)^t}} \tag{35}$$

$$f_{income} = \frac{EAC_{fuel} + EAC_{capital,user} + EAC_{maint}}{N_{families} \cdot 1{,}920 \cdot C_{labor}} \tag{36}$$

Incremental costs or cost effectiveness for greenhouse gas emission reductions or health improvements can be investigated.

$$C_{climate} = \frac{EAC_{total}}{GWC_{total}} \tag{37}$$

$$C_{health} = \frac{EAC_{total}}{RHI} \tag{38}$$

The cost of greenhouse gas savings can be compared to the market value for carbon offsets, C_{tCO2e}.

The output file is then created and includes reporting the range of outcome metrics (Eqns. 2-38) for each strategy, separated by the applicable energy services including cooking, water heating, lighting, and so on.

CHAPTER 5

THE IMPACTS OF POTENTIAL HOUSEHOLD ENERGY STRATEGIES

A major goal of this research is to understand which strategies are most effective to provide an improvement in energy services for a given community, whether those strategies include cookstoves, cleaner fuels, or improved devices for heating water or lighting. To achieve this goal, the model developed in Chapter 4 is used to explore a set of strategies based on commonly available generalized types of technologies to provide energy services to the household sector in the Malian village. In addition to analysis of the baseline (no intervention) scenario, six single-device strategies which represent a common approach in energy development projects are explored. These include the provision of improved biomass cookstoves, biomass cookstoves with advanced performance levels, communal cookstoves for cooking, LPG cookstoves, solar water heaters, and a community solar charging lighting system. In addition, an integrated, multiple-device strategy is then developed based on a combination of the most effective of these to build upon the natural user tendency to add new technologies to their current practices as availability and income allow. Often these additional technologies are targeted at specific end uses and are adopted when they clearly offer effective, convenient, and desirable energy services. These single-device and integrated strategies are shown in Table 5.1.

Table 5.1 Strategies for household energy services

		Single-technology						
	Baseline	**Improved**	**Advanced**	**Communal**	**LPG**	**Solar Water Heating**	**Solar Lighting**	**Integrated**
Cooking	TSF	Improved	Advanced	Communal	LPG	TSF	TSF	Advanced
Specialty cooking	TSF	Improved	Advanced	TSF	LPG	TSF	TSF	LPG
Water heating	TSF	Improved	Advanced	TSF	LPG	SWH	TSF	SWH
Space heating	TSF	TSF	TSF	TSF	TSF	TSF	TSF	TSF
Lighting	Kerosene	Kerosene	Kerosene	Kerosene	Kerosene	Kerosene	Solar	Solar

In the analyses, the technologies in each strategy are supplied for the entire village subject to displacement fraction and are used to complete the energy tasks to which they are assigned. Use of the baseline device is continued if not displaced by a new technology, and variables are all as described in Chapter 4. By default it is assumed that the baseline and the improved, advanced, and LPG cookstove strategies are applied to all cooking, specialized cooking, and water heating end uses; whereas the communal scenario is applied to cooking processes only, and the solar water heater is applied to water heating only with the remainder of tasks completed by the baseline three-stone fire. Space heating is included in the inventories although not affected by changes in technology in the present analysis.

The baseline scenario is compared to six of the most common single-device strategies currently under consideration by development organizations in order to inform the design and implementation process. These strategies include

(1) Baseline – Serving as the source of heat, light, and a central gathering place for tens of thousands of years, the traditional three-stone fire is used indoors or out, at high and low power, using a variety of fuels and cooking implements. Cooks can expertly operate it most effectively to meet their various needs. In its most common form, the traditional fire consists of three carefully selected stones used to support a cooking vessel over a fire built on the ground. In some cases, pot supports may be fashioned of metal or ceramic instead. In the baseline, the three-stone fire is used for cooking, all specialty cooking processes other than tea steeping (which is done on a traditional charcoal stove), outdoor water heating, and space heating. A kerosene wick lantern is used for lighting (Johnson and Bryden, 2012a).

(2) Improved biomass-fired cookstoves – Improved cookstoves of many types have been implemented by both governmental and non-governmental organizations for decades. Designs for improved stoves have varied widely, seeking to insulate and shield the fire from wind, elevate the fuelbed on a grate to provide improved primary air flow, and direct heat more efficiently into the cooking vessel by elevating it above the enclosed fire and providing channels for the flow of combustion gases. These designs often include enclosed combustion chambers made of metal or ceramic, engineered pot supports and shields to provide flow channels, and relatively small fuel entrances to limit the quantity of fuel that can be burned and thus the firepower. Examples of popular improved cookstoves include the VITA stove (Baldwin, 1987), the rocket stove and its many iterations, and stoves designed for the historic national stove programs of India and China. The fuel use of these stoves can be from half to equal that (or more) of the three-stone fire and emissions up to a 75% savings from that of the three-stone fire (MacCarty, Still and Ogle, 2010).

(3) Advanced biomass-fired cookstoves – More recently, research has been focused on development of advanced cookstoves that are more than 40% efficient and have significantly reduced emissions. These stoves are designated as ‘Tier 4’ or ‘aspirational’ in the ISO International Working Agreement (IWA) performance standards that are currently under development. These standards prescribe efficiency, carbon monoxide, and particulate matter emissions levels that approach that of modern fuels such as LPG (ISO, 2012). Designs that meet these criteria often utilize highly engineered techniques such as integral pots, controlled primary and secondary air flow, prepared fuels such as pellets, and forced draft provided by small electric fans.

(4) Communal biomass-fired cookstoves – Community-sized cookstoves have been designed to efficiently cook large quantities of food in settings such as schools and orphanages. These typically utilize a large (60-100 L) pot integrated into a specialized stove body with a chimney that directs smoke out of the cooking area. The surface area of the large pot and its high capacity offers economies of scale and therefore reduced fuel use and emissions per quanitity of food prepared. In some cultures, such as those with large extended families or special situations such as camps for displaced persons, communal cooking may be an acceptable strategy for household cooking as well. In the case of Sahel communties, nearly one-half of the population already cooks communally due to social structure based on large family groups. In other cultures, communal household cooking may not be preferred.

(5) LPG cookstoves – LPG is the fuel of choice in wealthy households without piped gas or electricity. It is clean burning, convenient, flexible, and more than 50% efficient. However, in subsistence-level households, the ability to purchase any fuel is limited, and even in lower- to middle- income households, the high upfront cost of purchase by the cylinder is often prohibitive. In rural communities, the lack of distribution infrastructure limits access and increases price relative to that of urban communities.

(6) Solar water heaters – A visible marker of income level seen on the rooftops of many households in developing countries, solar water heaters are often one of the first sought-after energy purchases as income allows. Solar water heaters include a solar collector system and a water storage system, and can be bought off the shelf or built from fairly simple materials. These solar thermal devices provide essentially free hot water for years with minimal maintance or cost after installation and can be operated at the household or

communal level. They require essentially no time to operate and are extremely convenient in cases where a filling method is available.

(7) Community-charged solar fluorescent lighting – Household lighting is one of the most well-known energy services, allowing for social, productive, and educational activities after sunset. This lighting can range from fuel-based lighting sources to battery power, solar lanterns, solar home systems, charged batteries, and micro-grid or grid power. Because many households desire greater output than a single solar LED lantern can provide, and household solar systems are more capital-, educationally-, and maintenance-intensive than centralized stations, community charged lead acid batteries are an excellent method of providing affordable energy for lighting in off-grid communities. In these systems, a community-centered charging station is operated by a member of the local community who is responsible for charging the batteries and supplying them to households for a small fee for each charge. Meanwhile the lighting systems are installed in the homes, which include several linear flourescent bulbs as needed (Sloan, Bryden, and McCorkle, 2012).

(8) An integrated strategy – Households in developed countries enjoy dozens of specialized energy devices to meet their energy needs, including stoves, ovens, water heaters, microwaves, popcorn poppers, bread machines, and charcoal barbeques. Evidence of this device ‘stacking’ has been seen in developing countries as well, where consumers optimize their resources to procure and use the most efficient, convenient, and effective for each task. As a result, an integrated strategy represents a natural progression to collect multiple devices as availability and income allow. This represents a user-driven strategy that begins with a device that meets the goals identified to be the most important to a

given consumer base, whether it be improved lighting, reduced indoor air pollution, or less fuel collection.

5.1 Analysis of the Baseline Scenario

In the baseline scenario, different end uses contribute disproportionately to the energy use, climate and health effects, and cost of energy services. An important, yet often unaddressed, question is which of the major end uses to target given the optimal performance of different devices for different end uses. Figure 5.1 shows the estimated contributions of the various energy uses to the overall impacts in the baseline scenario. Note that the climate impacts include Kyoto and non-Kyoto species on a 100-year timeframe.

Cooking meals represents approximately half of total energy use in the household with an additional ~10% for specialty cooking processes such as making tea and medicine. Water heating and space heating each consume approximately 20% of energy, and the share of energy consumed for lighting is essentially negligible. In terms of cost, however, lighting represents nearly 20% due to the purchase of commercial kerosene when the opportunity cost of time spent collecting fuelwood is included. If the cost of fuel collection time was not included, the purchase of kerosene and maintenance of the kerosene lanterns would represent 100% of the monetary energy expense in the household. This does not include the cost of disposable batteries for portable devices such as flashlights not considered in this analysis but representing a cost of $3,816 per year in the Malian village (Johnson and Bryden, 2012a). Lighting also plays a significant role in climate impact, primarily because the emissions of black carbon from kerosene wick lighting are an order of magnitude higher than that of cooking (Lam et al., 2012). Cooking, water heating, and lighting continue to contribute their proportional share to climate impacts.

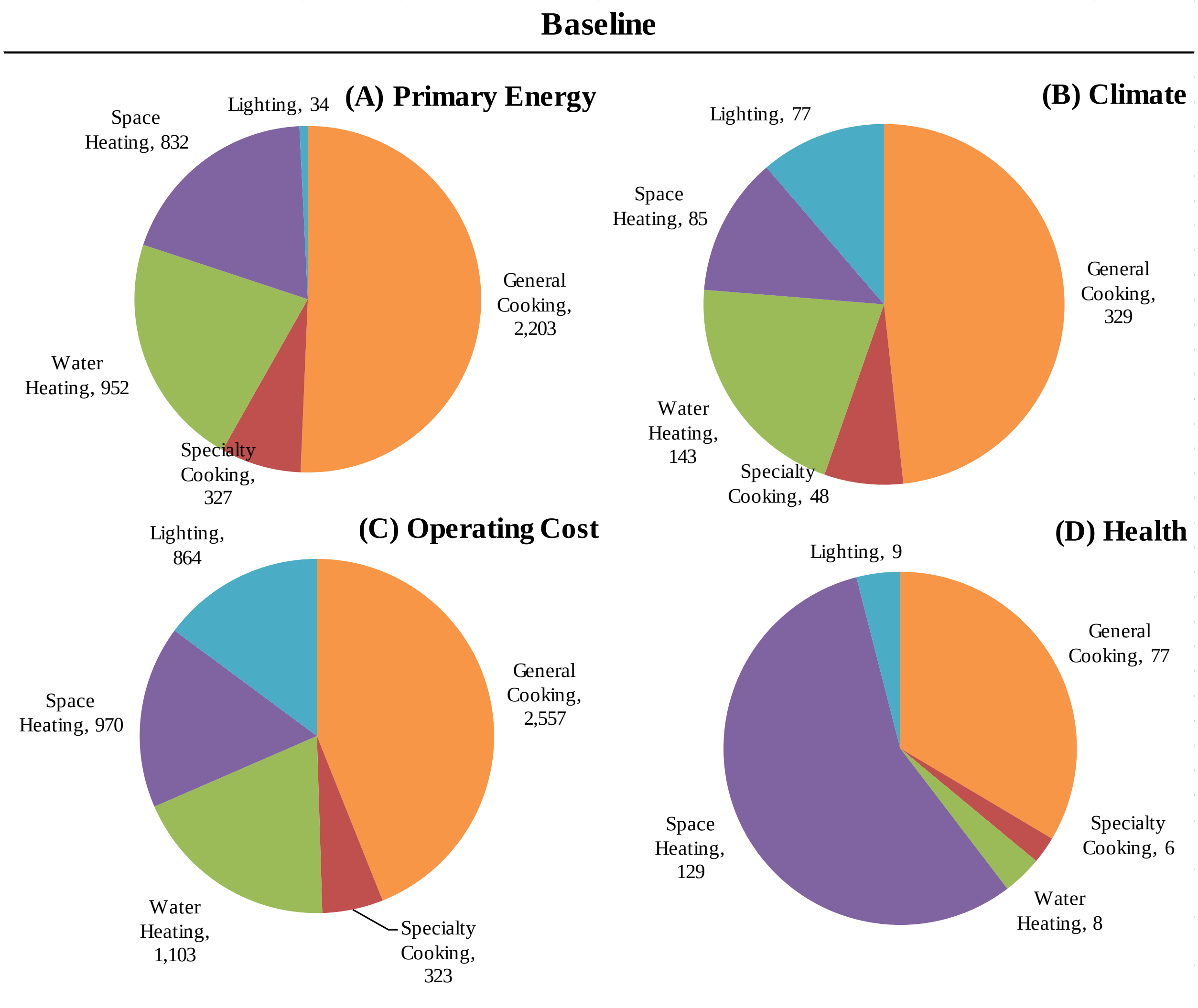

Figure 5.1 Analysis of the baseline scenario in terms of (A) Primary energy consumption (GJ/y), (B) Climate impact (tCO2e/y), (C) Operating cost ($US/y) including fuel purchase and collection time, and (D) Health impact (1000*RHI/y)

For health, however, these representative shares are skewed significantly due to accounting for their indoor/outdoor attributes. Space heating is conducted indoors with no ventilation applied, and the emission factors of unattended heating fires were measured as approximately two times that of cooking fires in the literature (Bhattacharya,Abdul Salam, and Sharma, 2000). As a result, the contribution of heating to health risks surpasses that of cooking using these figures. The health risks of water heating, however, are minimal due to the high level of ventilation applied when heating water outdoors.

This analysis of the baseline scenario illustrates the conflicting objectives that challenge village energy programs. For example, it appears that cooking would be the energy need to target if the goal is to reduce energy consumption. However, if the objective is to reduce cost to the user (often the primary goal of the user), reducing the expenses for lighting would be the optimal path. Although cooking represents the largest share of climate, perhaps a solar water heater that eliminates emissions from water heating would be a better option than a cookstove that incrementally reduces emissions for cooking tasks. Finally, providing a method for space heating or other options for keeping elders warm (such as blankets) that reduce or eliminate household air pollution would provide the largest impact on health given the assumptions used here.

5.2 Analysis of the Six Single-technology Scenarios

As was seen regarding the differing impacts created by different energy services on the variety of outcomes, divergent technology strategies will have varying impacts on the categories of objectives. These are investigated in this section. Note that in this analysis, lighting accounts for the multifunctional nature of the three-stone fire to include the additional kerosene needed when a new technology no longer provides firelight in the home during dinner. And for the solar lighting system, payments for recharging the batteries are treated as maintenance rather than fuel costs. The data all assume 100% displacement of the potential technology. Operating cost is reported for consumable fuels, and opportunity cost of time associated with each energy use, and excludes the purchase of durable devices, maintenance, and recharging of batteries. The embodied energy and emissions resulting from the manufacture and implementation of devices are not included in this analysis. Outcomes are reported in terms of primary energy, climate, operating cost, and health impacts. Quality of life is another important outcome, but due to the weighting system of this qualitative metric, graphical comparison is not provided.

5.2.1 Improved biomass cookstoves

In this scenario, improved cookstoves are used to provide cooking, specialty cooking, and water heating services. As shown in Figure 5.2, improved cookstoves as a single intervention at 100% displacement can save nearly 25% of primary energy, 20% of health and 10% of climate impact, and a small fraction of operating cost through time savings. These overall savings represent modest impacts on cooking and water heating services. Because the improved cookstoves limit the multi-functional lighting provided by the three-stone fire, lighting requirements are increased as are their associated emissions and cost impacts. The auxiliary services provided by the three-stone fire are also reduced due to the lowered fuel consumption due to increased cooking efficiency, therefore heating requirements and impacts are also increased slightly. In addition, the relatively short expected life (2 years) of the cookstoves makes the outcomes short-lived. The social quality of life metric sees a reduction from 5.0 to 4.5 due to the lowered convenience and change in practice required.

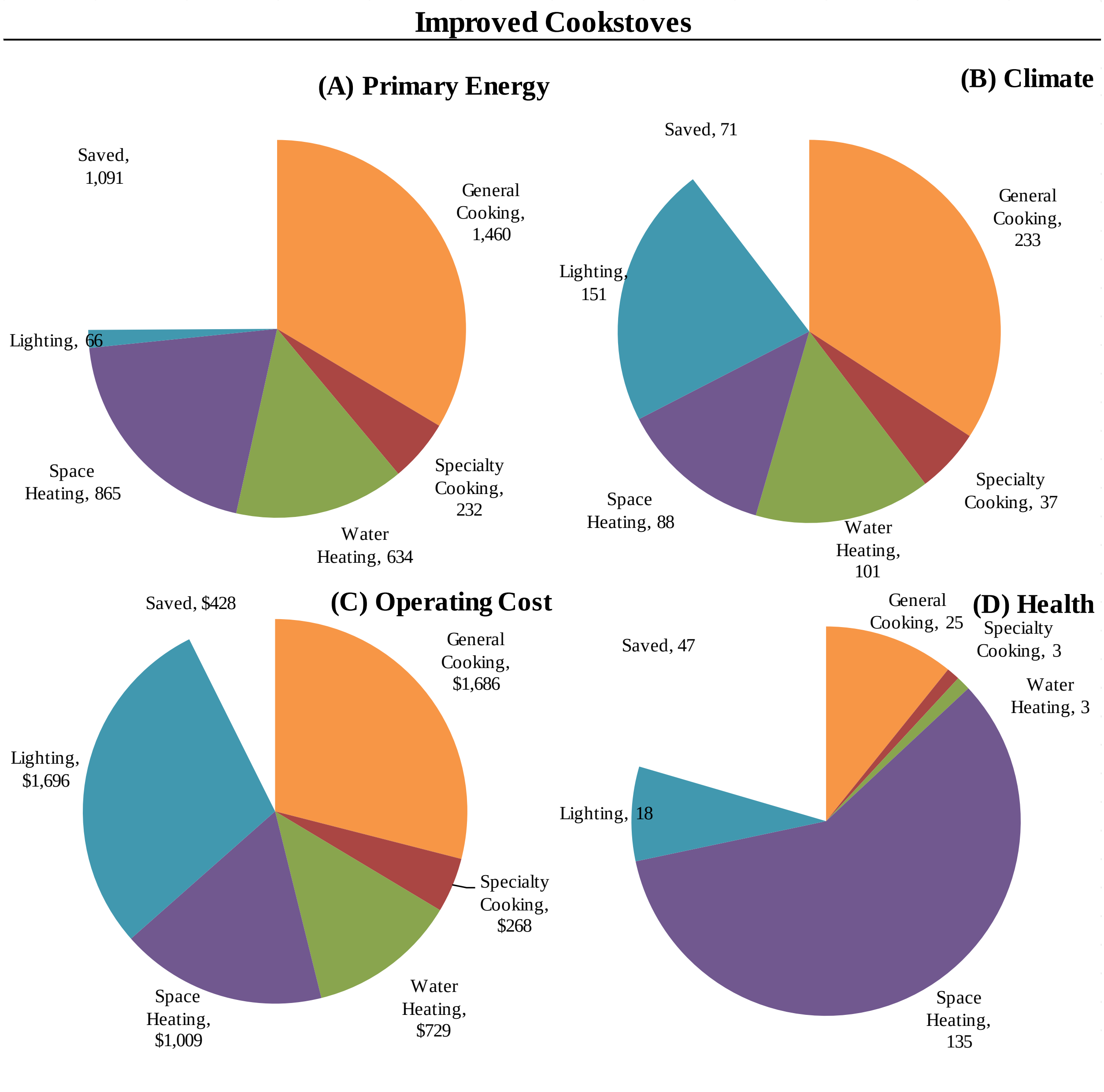

Figure 5.2 Analysis of the improved cookstoves strategy in terms of (A) Primary energy consumption (GJ/y), (B) Climate impact (tCO2e/y), (C) Operating cost ($US/y) including fuel purchase and collection time, and (D) Health impact (1000*RHI/y)

5.2.2 Advanced biomass cookstoves

In this scenario, advanced cookstoves are used to replace the three-stone fire for cooking, specialty cooking, and water heating; however, it is likely the highly engineered designs are better suited to a more narrow range of tasks. Figure 5.3 shows the best-case scenario of displacing the three-stone fire for all three types of tasks.

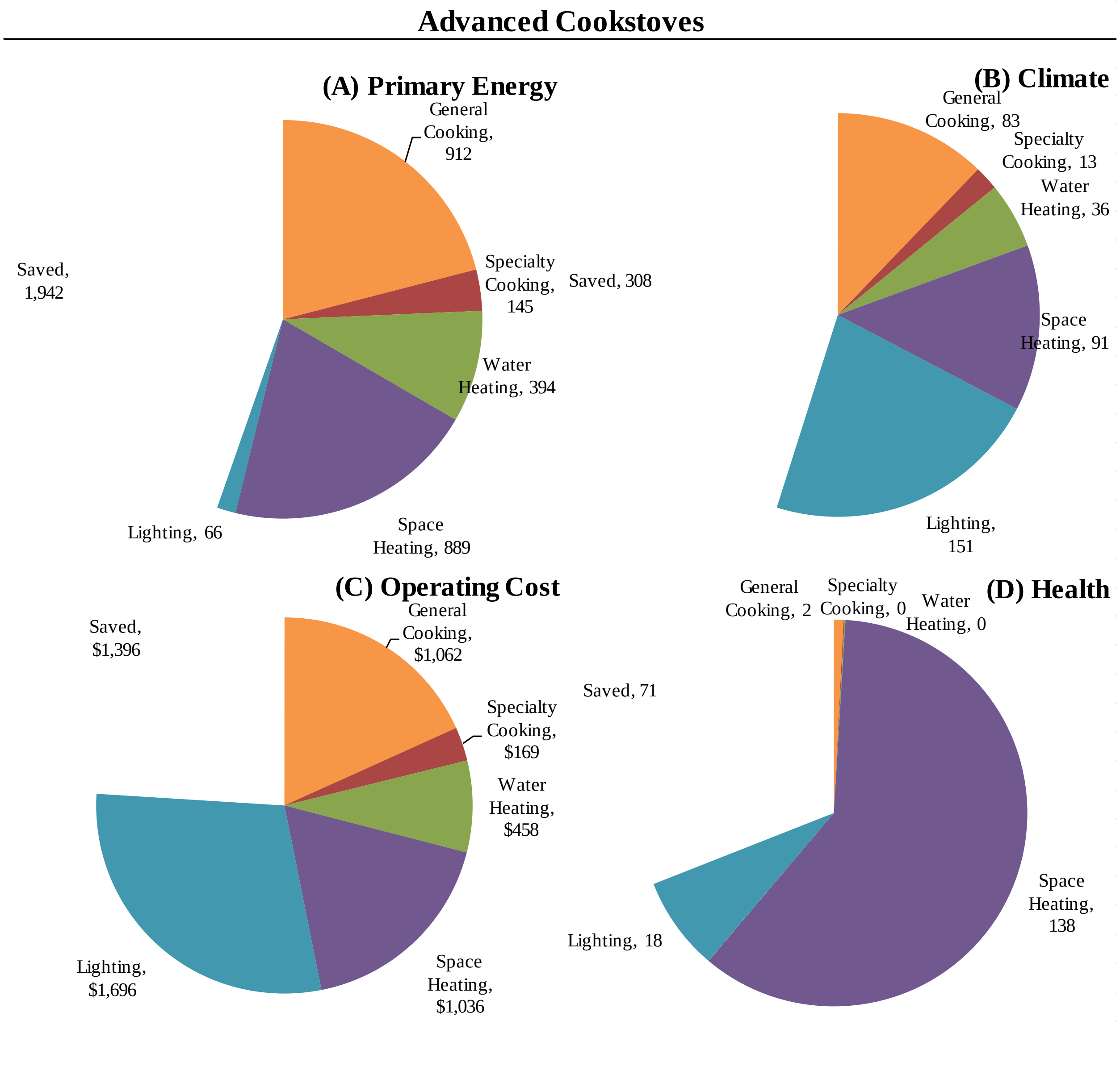

Figure 5.3 Analysis of the advanced cookstoves strategy in terms of (A) Primary energy consumption (GJ/y), (B) Climate impact (tCO2e/y), (C) Operating cost ($US/y) including fuel purchase and collection time, and (D) Health impact (1000*RHI/y)

The advanced stove offers more substantial savings for all metrics, saving nearly 40% of energy and climate, 30% of health, and offering nearly a 25% reduction in operating cost due to its high efficiency if used for all three energy services at 100% displacement. Advanced stove status dictates that emission rates approach those of LPG cookstoves for CO and PM as prescribed by the ISO Tier 4 standard. This level of clean burning virtually eliminates the health impacts relative to the baseline for the cooking and water heating services (ISO, 2012). Lighting and heating requirements again increase due to lost multi-function. The social quality of life metric sees a slight increase from 5.0 to 5.3 due to the lowered convenience but increased desirability of the advanced cookstoves.

5.2.3 Communal cooking

In this scenario, large (60 liter or more) cookstoves are used for preparing meals. Although communal cookstoves may be suited to preparing large pots of sauces, stews, or grains, they are most likely not suited to the specialty tasks conducted in each household, such as steeping tea, making medicine as needed, and roasting peanuts. Water heating could be conducted on communal cookstoves; however, the large volume of wash water required (about 10L per person per day from Johnson (2012)) relative to food cooked would likely require an unreasonable quantity of the community-sized stoves. Therefore, the results presented in Figure 5.4 show the impacts of a communal stove used for cooking only. The communal stove has performance levels similar to that of the advanced stove, and it includes a chimney. Because it is used for cooking only, expected savings are substantial but not as significant as those of the advanced stove. Due to the use of a chimney, the communal stove virtually eliminates the health risks from cooking. Since the stove is not used in the home, no contributions are made to heating and lighting. The social quality of life metric sees a reduction from 5.0 to 4.8 due to the increased convenience but significant change in practice required.

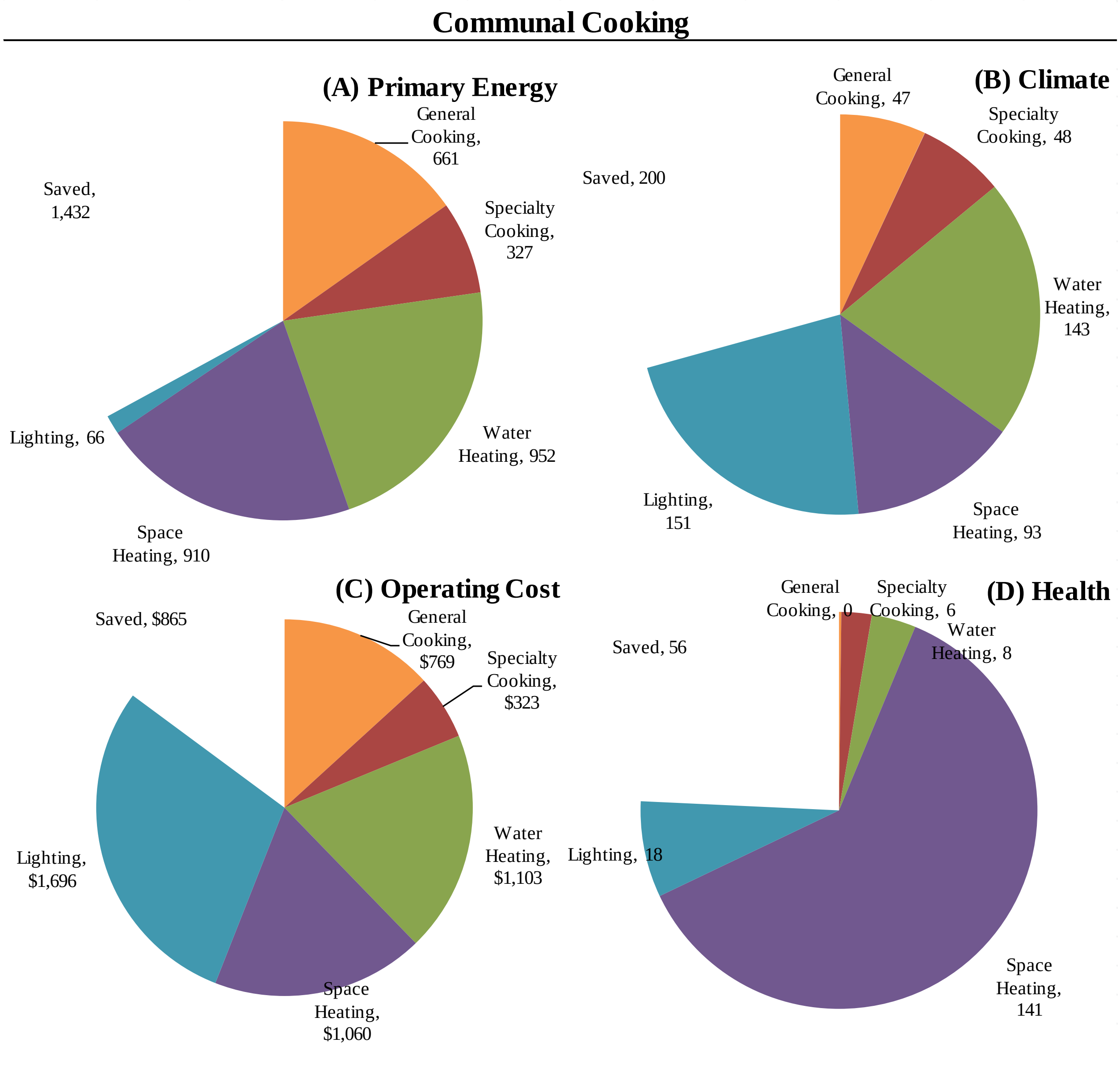

Figure 5.4 Analysis of the communal cooking strategy in terms of (A) Primary energy consumption (GJ/y), (B) Climate impact (tCO2e/y), (C) Operating cost ($US/y) including fuel purchase and collection time, and (D) Health impact (1000*RHI/y)

5.2.4 LPG Cookstoves

The use of LPG cookstoves for all thermal tasks is often the strategy of choice in the case of households that can afford it because it represents the cleanest and most convenient option. If

LPG were to replace biomass for all cooking, specialty cooking, and water heating processes (although not space heating or lighting), the effects would be as shown in Figure 5.5.

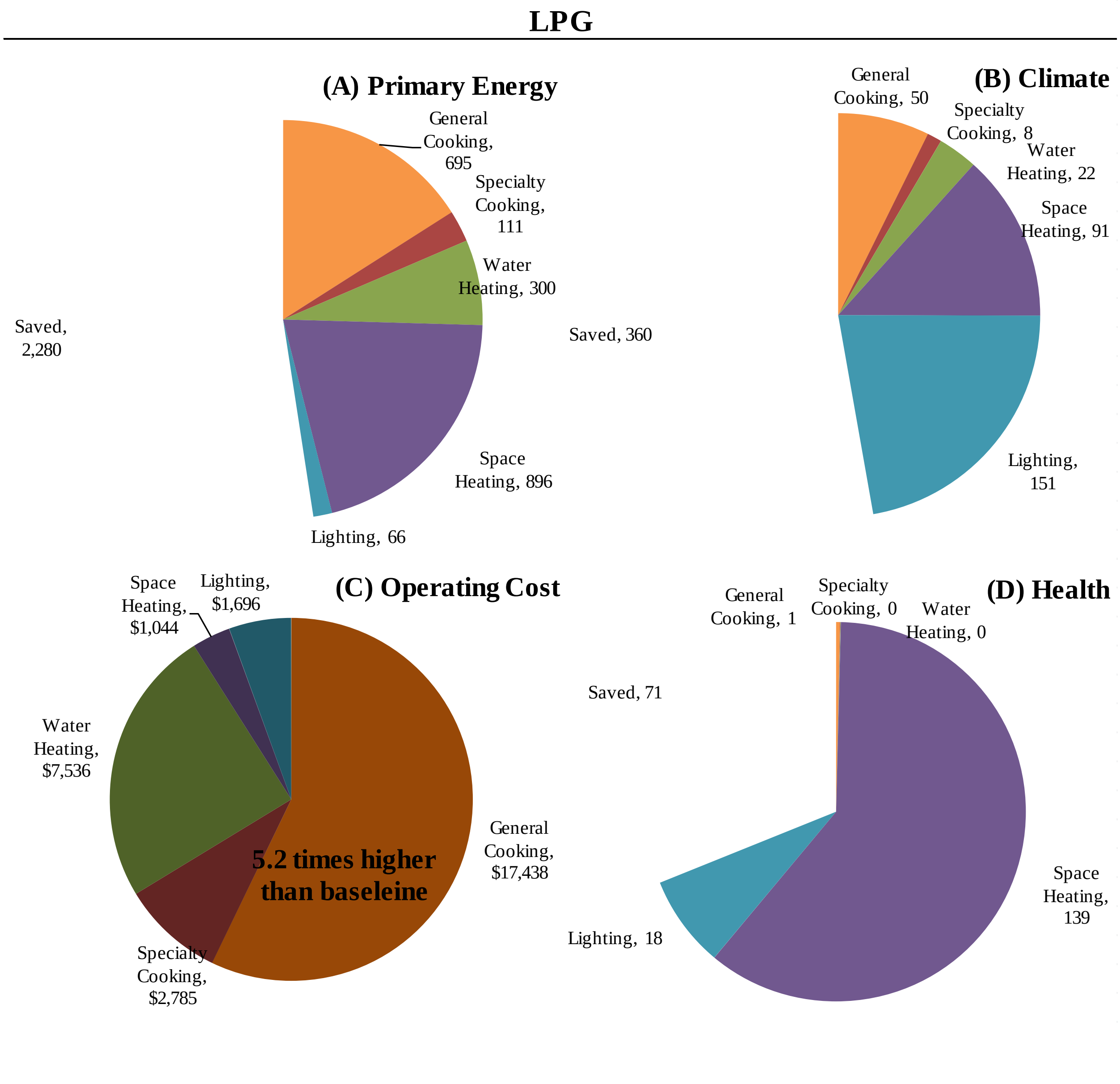

Figure 5.5 Analysis of the LPG cookstove strategy in terms of (A) Primary energy consumption (GJ/y), (B) Climate impact (tCO2e/y), (C) Operating cost ($US/y) including fuel purchase and collection time, and (D) Health impact (1000*RHI/y)

Due to the high thermal efficiency (>50%) and low emissions from LPG cookstoves, this strategy offers the largest impacts of all of the thermal devices for cooking processes, saving more than half of the energy and climate impacts, and nearly eliminating the health impacts from cooking and water heating. The operating cost chart is noted in a darker color because, due to the high cost of this commercial fuel, total operating costs actually increase to over 525% of the baseline. The quality of life metric sees significant improvement to 8.2 due to the aspirational nature of LPG. Thus, LPG cookstoves are an ideal solution in terms of every objective with the exception of operating cost.

5.2.5 Solar water heating

The impact of solar water heaters supplied throughout the village such that each person is provided with 10 liters of hot water per day is shown in Figure 5.6. The primary energy and emissions from water heating are eliminated entirely through the use of solar energy when the life cycle and implementation of the devices are not considered. And because use of the three-stone fire for cooking is not impacted, lighting and heating requirements revert to the baseline. So the water heating slice of each chart is simply removed with all else equal to the baseline. The long expected life (15 years) of these devices makes the solution sustainable in the long term as well. The quality of life for water heating is optimal at 10 with such a convenient, safe, and desirable device.

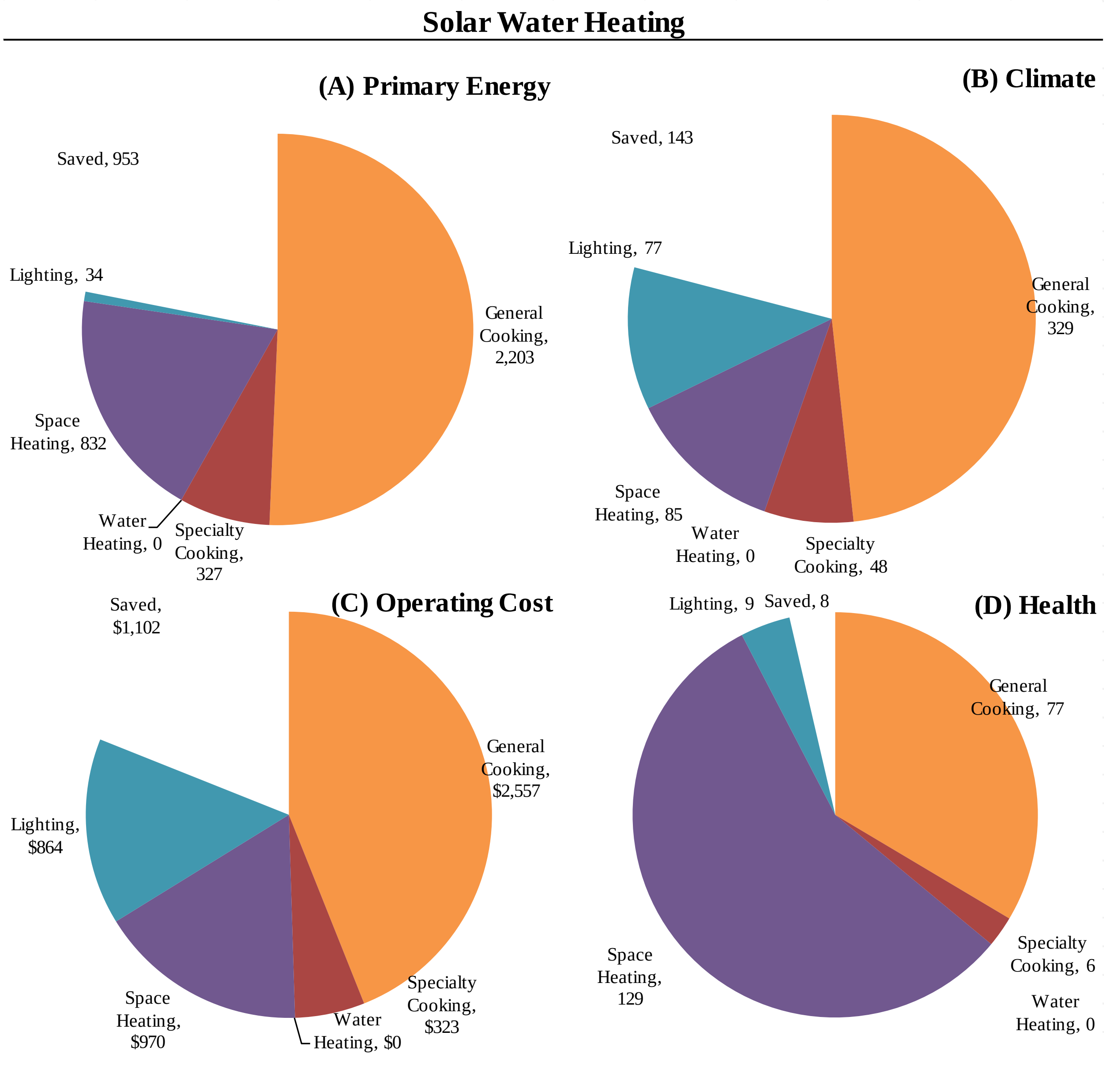

Figure 5.6 Analysis of the solar water heating strategy in terms of (A) Primary energy consumption (GJ/y), (B) Climate impact (tCO2e/y), (C) Operating cost ($US/y) including fuel purchase and collection time, and (D) Health impact (1000*RHI/y)

5.2.6 Solar lighting

Finally, the application of improved lighting services, although addressing a much smaller need in terms of energy, can help to achieve one of the users most sought-after developments for modern lighting services to allow for productivity, education, safety, and socializing after sunset. The impacts of this in terms of the quantitative objectives are shown in Figure 5.7.

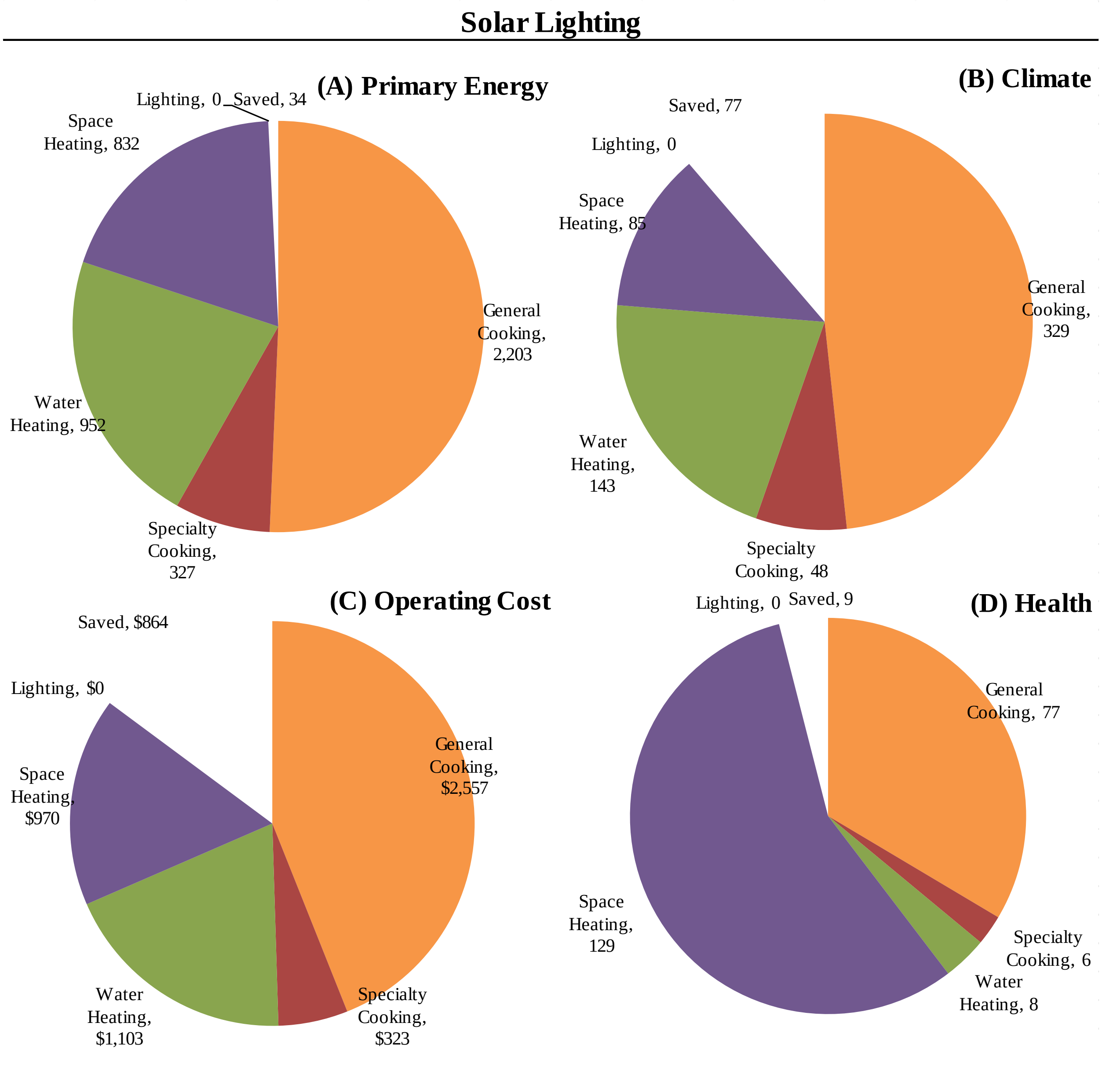

Figure 5.7 Analysis of the solar lighting strategy in terms of (A) Primary energy consumption (GJ/y), (B) Climate impact (tCO2e/y), (C) Operating cost ($US/y) including fuel purchase and collection time, and (D) Health impact (1000*RHI/y)

Although the use solar energy for lighting does not have a large impact on overall primary energy consumption in the village, the elimination of the use of polluting kerosene for lighting reduces climate impacts by approximately 10% and health impacts by about 15%. The cost to purchase the kerosene is also eliminated, which represents a savings of about 20% relative to the opportunity costs of fuelwood collection. In terms of purely monetary costs, the purchase of kerosene is the only monetary operating cost in the village. This, however, would be replaced by the cost of recharging batteries in the community, which is not shown in this chart because it is treated as a maintenance cost rather than a fuel cost. The quality of life for lighting is optimized.

5.2.7 Summary

The outcomes of these strategies are collected and summarized in Table 5.2. The most significant improvement in each use and outcome category is underlined in bold green in order to compare the optimal strategy in each category. This shows that for general cooking, the best technology in terms of all five outcomes is communal cooking followed by LPG. For specialty cooking LPG is the best strategy, except in terms of operating cost in which case the advanced cookstove is preferred. The best technology for water heating is clearly the solar water heater and for lighting is the solar lighting system. For quality of life measures, as expected, the solar water heater is most effective followed by LPG, and the solar lighting system would be if village-scale weighting was based on a value other than energy use. Given these clearly differing optimal strategies for the array of energy service needs in the village, there is no single strategy that provides the best solution. Therefore, development of a multiple-technology, integrated solution is likely needed to most effectively meet all of the objectives.

Table 5.2. Key outcomes by end use, with 95% confidence interval for 1000 iterations

	Baseline	Improved	Advanced	Communal	LPG	Solar Water	Solar Lighting
PRIMARY ENERGY (GJ/y)	*4,349*	*3,258*	*2,407*	*2,917*	*2,069*	*3,396*	*4,315*
General Cooking	2,203 ± 34	1,460 ± 39	912 ± 19	**661** ± 13	695 ± 6	2,203 ± -	2,203 ± -
Specialty Cooking	327 ± 5	232 ± 7	145 ± 3	327 ± -	**111** ± 1	327 ± -	327 ± -
Water Heating	952 ± 14	634 ± 20	394 ± 11	952 ± -	300 ± 3	**0** ± 0	952 ± -
Space Heating	832 ± 13	865 ± 13	889 ± 13	910 ± 13	896 ± 13	832 ± -	832 ± -
Lighting	34 ± 0	66 ± 1	66 ± 1	66 ± 1	66 ± 1	34 ± -	**0** ± 0
CLIMATE (tCO_2e/y)	*682*	*611*	*374*	*482*	*322*	*539*	*605*
General Cooking	329 ± 7	233 ± 7	83 ± 5	**47** ± 1	50 ± 1	329 ± -	329 ± -
Specialty Cooking	48 ± 1	37 ± 1	13 ± 1	48 ± -	**8** ± 0	48 ± -	48 ± -
Water Heating	143 ± 3	101 ± 4	36 ± 2	143 ± -	22 ± 0	**0** ± 0	143 ± -
Space Heating	85 ± 2	88 ± 2	91 ± 2	93 ± 2	91 ± 2	85 ± -	85 ± -
Lighting	77 ± 0	151 ± 12	151 ± 12	151 ± 12	151 ± 12	77 ± -	**0** ± 0
HEALTH (RHI as 1000m3/y)	*230*	*183*	*158*	*174*	*158*	*221*	*220*
General Cooking	77 ± 2	25 ± 1	2 ± 0	**0** ± 0	1 ± 0	77 ± -	77 ± -
Specialty Cooking	6 ± 0	3 ± 0	0 ± 0	6 ± -	**0** ± 0	6 ± -	6 ± -
Water Heating	8 ± 0	3 ± 0	0 ± 0	8 ± -	0 ± 0	**0** ± 0	8 ± -
Space Heating	129 ± 2	135 ± 2	138 ± 2	141 ± 2	139 ± 2	129 ± -	129 ± -
Lighting	9 ± 0	18 ± 0	18 ± 0	18 ± 0	18 ± 0	9 ± -	**0** ± 0
OPERATING COST ($US/y)	*5,816*	*5,388*	*4,420*	*4,951*	*30,498*	*4,714*	*4,953*
General Cooking	2,557 ± 81	1,686 ± 64	1,062 ± 38	**769** ± 27	17,438 ± 308	2,557 ± -	2,557 ± -
Specialty Cooking	323 ± 10	268 ± 10	**169** ± 6	323 ± -	2,785 ± 55	323 ± -	323 ± -
Water Heating	1,103 ± 34	729 ± 30	458 ± 18	1,103 ± -	7,536 ± 133	**0** ± 0	1,103 ± -
Space Heating	970 ± 31	1,009 ± 33	1,036 ± 33	1,060 ± 34	1,044 ± 33	970 ± -	970 ± -
Lighting	864 ± 0	1,696 ± 35	1,696 ± 35	1,696 ± 35	1,696 ± 35	864 ± -	**0** ± 0
QUALITY OF LIFE							
General Cooking	5.0 ± -	4.5 ± 0.03	5.3 ± 0.03	4.8 ± 0.03	**8.2** ± 0.03	5.0 ± -	5.0 ± -
Specialty Cooking	5.0 ± -	4.5 ± 0.03	5.3 ± 0.03	5.0 ± -	**8.2** ± 0.03	5.0 ± -	5.0 ± -
Water Heating	5.0 ± -	4.5 ± 0.03	5.3 ± 0.03	5.0 ± -	8.2 ± 0.03	**10.0** ± 0.03	5.0 ± -
Space Heating	5.0 ± -	5.0 ± 0.03	5.0 ± 0.03	5.0 ± 0.03	5.0 ± 0.03	5.0 ± -	5.0 ± -
Lighting	5.0 ± -	5.0 ± 0.03	5.0 ± 0.03	5.0 ± 0.03	5.0 ± 0.03	5.0 ± -	**9.5** ± 0.03

5.3 Development of an Integrated Strategy

Often a single technology-based approach is taken for the provision of energy services for developing countries, with implementation efforts focusing on generating demand for and installing a single technology such as a cookstove or lighting system. However, as was seen in the analysis in Section 5.2, there is no single technology that provides the optimal solution in terms of all five objectives. And further, not all technologies can optimally provide each of the energy services to which they are assigned. Therefore, a multiple-technology strategy may be required to provide the optimal outcomes in all categories. In order to develop this, Table 5.3 presents a feasibility analysis of each strategy with the net benefits for each of the five outcomes for the village each year. The gray boxes indicate the use/technology pairs that are not expected to be feasible or acceptable and therefore that energy usage would revert to the baseline methods. For example, an advanced cookstove is generally designed for a specific size of pot and firepower level. Therefore, it will not likely be used for water heating or suited for specialized tasks such as roasting peanuts or processing shea. Communal cooking in large pots is not suited for specialized processes or heating water for bathing. LPG is not necessary for heating water, which is generally done outdoors, and the cost of LPG is generally prohibitive for intensive tasks such as heating water and cooking. However, people often switch to LPG for small specialty tasks when possible.

This leaves only a few possible comprehensive strategies that can address more than one or two energy needs at a time. The first of these is the use of a single device with a design that is flexible enough to meet the three thermal needs of cooking, specialty cooking, and water heating while continuing to use the traditional kerosene lantern and heating stove. A general improved cookstove that can accommodate multiple pot sizes, fuel conditions, and tending procedures could accomplish this.

Table 5.3 Feasibility of six technology strategies

	Technology Strategy					
	Improved	Advanced	Communal	LPG	SWH	Lighting
PRIMARY ENERGY SAVINGS (GJ/y)						
General Cooking	743	1,291	1,542	1,508	0	0
Specialty Cooking	95	182	0	216	0	0
Water Heating	319	558	0	652	952	0
Lighting	-33	-33	-33	-33	0	34
	1,157	1,291	1,542	216	952	34
CLIMATE SAVINGS (tCO2e/y)						
General Cooking	96	246	282	279	0	0
Specialty Cooking	11	35	0	40	0	0
Water Heating	41	107	0	121	143	0
Lighting	-74	-74	-74	-74	0	77
	149	246	282	40	143	77
HEALTH SAVINGS (RHI as m3/y)						
General Cooking	52	75	77	76	0	0
Specialty Cooking	3	5	0	6	0	0
Water Heating	6	8	0	8	8	0
Lighting	-9	-9	-9	-9	0	9
	61	75	77	6	8	9
OPERATING COST SAVINGS ($US/y)						
General Cooking	871	1,495	1,787	-14,881	0	0
Specialty Cooking	55	155	0	-2,461	0	0
Water Heating	373	645	0	-6,434	1,103	0
Lighting	-832	-832	-832	-832	0	864
	1,300	1,495	1,787	-2,461	1,103	864
QUALITY OF LIFE IMPROVEMENT						
General Cooking	-0.5	0.3	-0.2	3.2	0.0	0.0
Specialty Cooking	-0.5	0.3	0.0	3.2	0.0	0.0
Water Heating	-0.5	0.3	0.0	3.2	5.0	0.0
Lighting	0.0	0.0	0.0	0.0	0.0	4.5
	-1.5	0.3	-0.2	3.2	5.0	4.5

A second option, however, involves a multiple-device strategy based on the technologies that offer the largest impacts targeting each energy need. These are shown in the white boxes throughout Table 5.3. This would include use of biomass cookstoves for cooking, LPG for specialty cooking, solar water heaters for heating water, and a community-charged solar system for lighting. The need for space heating is not presently addressed here, but alternative methods for heating such as heating stoves, LPG burners, or even blankets may help reduce or eliminate the energy and emissions from space heating. Because the advanced cookstoves represent the largest impacts without the need for cooking communally, it is assumed to be the optimal technology to meet the needs for cooking. A combination of these four devices represents an integrated strategy which allows the user to meet each of their energy needs with a device best suited to provide that particular service, much in the way kitchens in developed nations have specialized devices for specific tasks such as ovens, stoves, water heaters, rice cookers, and popcorn poppers to name only a few.

5.4 Comparison of Eight Scenarios

The village-scale outcomes in terms of each of the various objectives for each single-technology strategy as well as the integrated strategy are compared in Figures 5.8 through 5.12. These present separate results for each of the eight potential scenarios as a function of displacement fraction for each of the five objectives including (1) primary energy consumption, (2) global warming commitment, (3) health, (4) equivalent annual cost, and (5) overall quality of life for the village as a whole as a function of displacement fraction for the eight scenarios. These figures illustrate that although it is known to be one of the greatest challenges, user adoption is arguably one of the most important factors dictating outcome. These figures can assist in understanding the level of adoption required for one technology to provide a larger impact relative to another.

5.4.1 Energy Consumption

In terms of primary energy consumption, solar water heaters and improved cookstoves are expected to offer statistically equal savings (Figure 5.8).

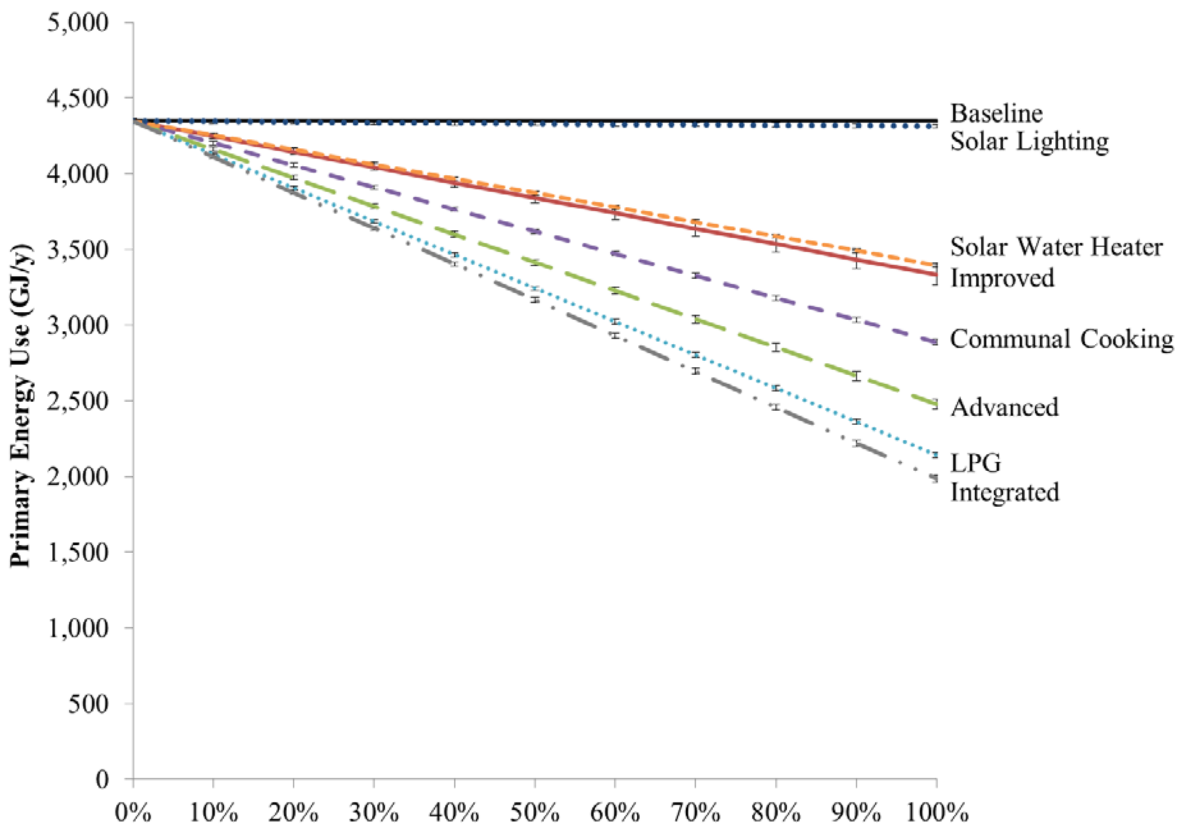

Figure 5.8 Primary energy consumption (GJ/y) as a function of displacement fraction, 95% confidence interval

Due to the high efficiency of LPG cookstoves, the LPG strategy offers the most energy savings of the single-technology strategies. Because the integrated strategy eliminates primary energy used for heating water and lighting in favor of solar resources, it offers savings even over LPG. It is likely the displacement fraction will vary widely for these technologies. For example, the solar water heater at full displacement assumed operation for 100% of the year, but there is a potential the water will not be sufficiently heated during the rainy season, thus reducing the displacement fraction to 75% or less. And communal cooking may be suitable during midday and evening meals but perhaps not for breakfast, reducing the displacement to about 70%. In this case both of these technologies would then potentially offer lower impacts than improved cookstoves that are widely adopted, for example. Research into how these technologies are actually used in the target community would be needed. Regardless, an integrated strategy that is fully adopted saves more than 50% of the primary energy consumed in the household.

5.4.2 Climate

The improved stove offers the lowest impact on climate because often improved cookstoves actually increase the ratio of warming black carbon to climate ‘cooling’ organic carbon (MacCarty et al., 2008). Similarly, despite offering negligible energy savings, the solar lighting system offers an equal impact due to the elimination of the kerosene wick-based lighting which, as shown in Table 4.2, produces extremely high emissions of black carbon. Solar water heaters at 100% displacement can reduce energy consumption by about 1 TJ/y and greenhouse gases by almost 150 tCO_{2e}/y. Because solar water heaters are convenient and desirable, 100% adoption can be expected given adequate financial ability and sufficient operation during the rainy season. However, to reach that level of energy and greenhouse gas savings, an advanced cookstoves would need to be adopted and consistently used for *all* cooking and water heating activities by 40% of the village – a target that may not be achievable considering most advanced cookstoves are likely not suited to water heating or specialty cooking and may be less convenient to operate than traditional methods. A more detailed analysis of the issues regarding usability is provided in Chapter 7. Although it is a fossil fuel and therefore its carbon dioxide emissions are included in the inventory, LPG cookstoves still offer the greatest climate impact in comparison to the other single energy technologies. The integrated strategy eliminates a substantial 75% of the total greenhouse gases in the household.

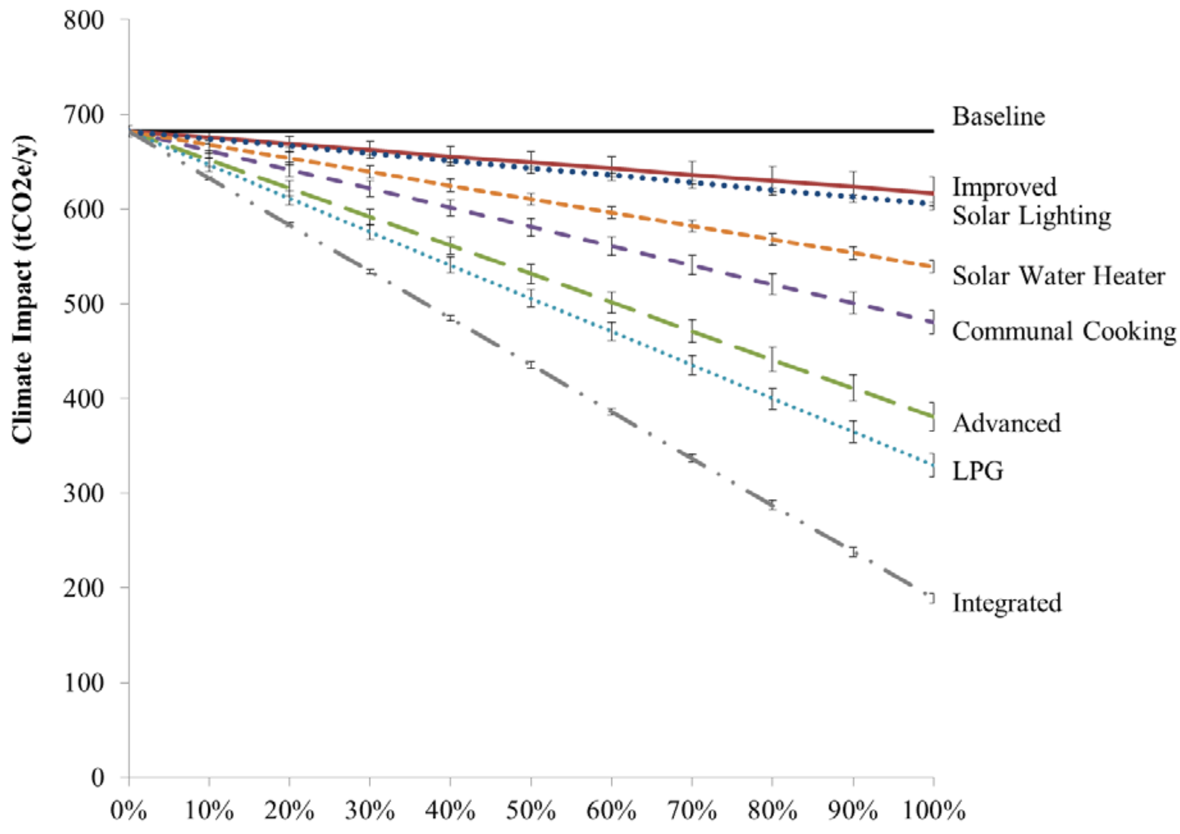

Figure 5.9 Climate impact (tCO_{2e}/y) as a function of displacement fraction, 95% confidence interval

5.4.3 Health

It is more difficult to impact health than it is to reduce energy consumption or greenhouse gas emissions. Even the integrated strategy is only able to reduce the relative hazard index by approximately 40%. This is due to the significant health impact of traditional space heating seen in section 5.1. If a heating stove with a chimney or operated from clean-burning fuel such as LPG were to replace the traditional heating fire, the health impacts would be substantial, yet the energy impact would be negligible because the heating efficiency is assumed to be 100% for the heating fire. Conversely, since water heating is already conducted primarily outside and this added ventilation is accounted for in health measures, a solar water heater has much less of an impact on health than climate.

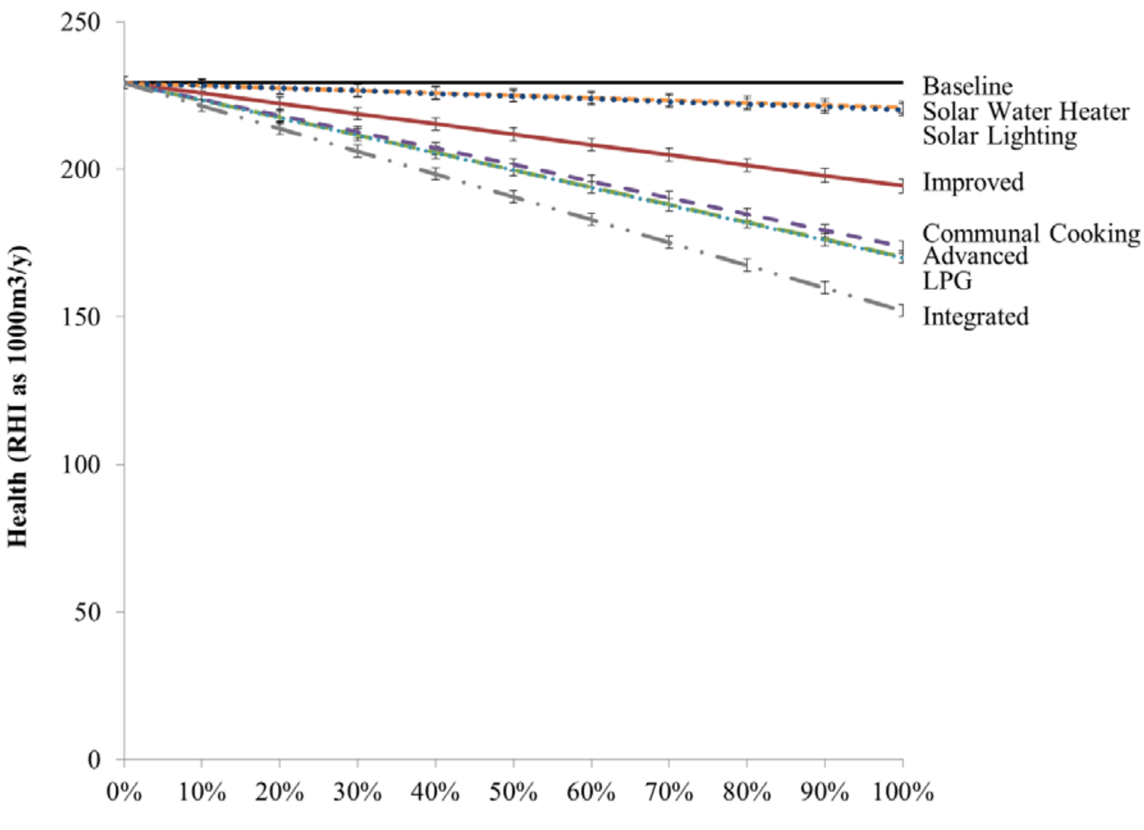

Figure 5.10 Health impact (Relative Hazard Index as 1000 m^3/y) as a function of displacement fraction, 95% confidence interval

As a result, an advanced cookstoves would require only about 10% displacement to generate a larger health impact than a solar water heater. An improved stove offers a median impact on health between the baseline and an advanced or LPG stove. If it were equipped with a functioning chimney, however, improved stove impacts could approach the health of those of LPG.

5.4.4 Cost

Unlike the previous analysis, which highlighted operating cost only, the equivalent annual cost predictions shown in Figure 5.11 includes the cost of fuel, the opportunity cost of fuel collection, the value of hours of added light for any income-producing activities, maintenance costs, and the annualized investment cost of purchase. Clearly LPG cookstoves are the most expensive option due to the high cost of imported commercial fuel. The integrated strategy, however, is only about one-half of that relative to the baseline despite requiring a more substantial capital investment in devices. Because the integrated strategy includes the value of income earned from improved lighting, the net total cost is only equal to that of the solar water heaters alone, which are the most expensive of all of the devices and are included in that integrated strategy. Due to savings in time to collect fuel, the communal, advanced, and improved cookstoves only cost a little bit more than the cost of the baseline scenario, which includes both time for fuel collection and the purchase of kerosene for lighting. It is interesting that at 100% displacement, the solar lighting system just about pays for itself through the income generated.

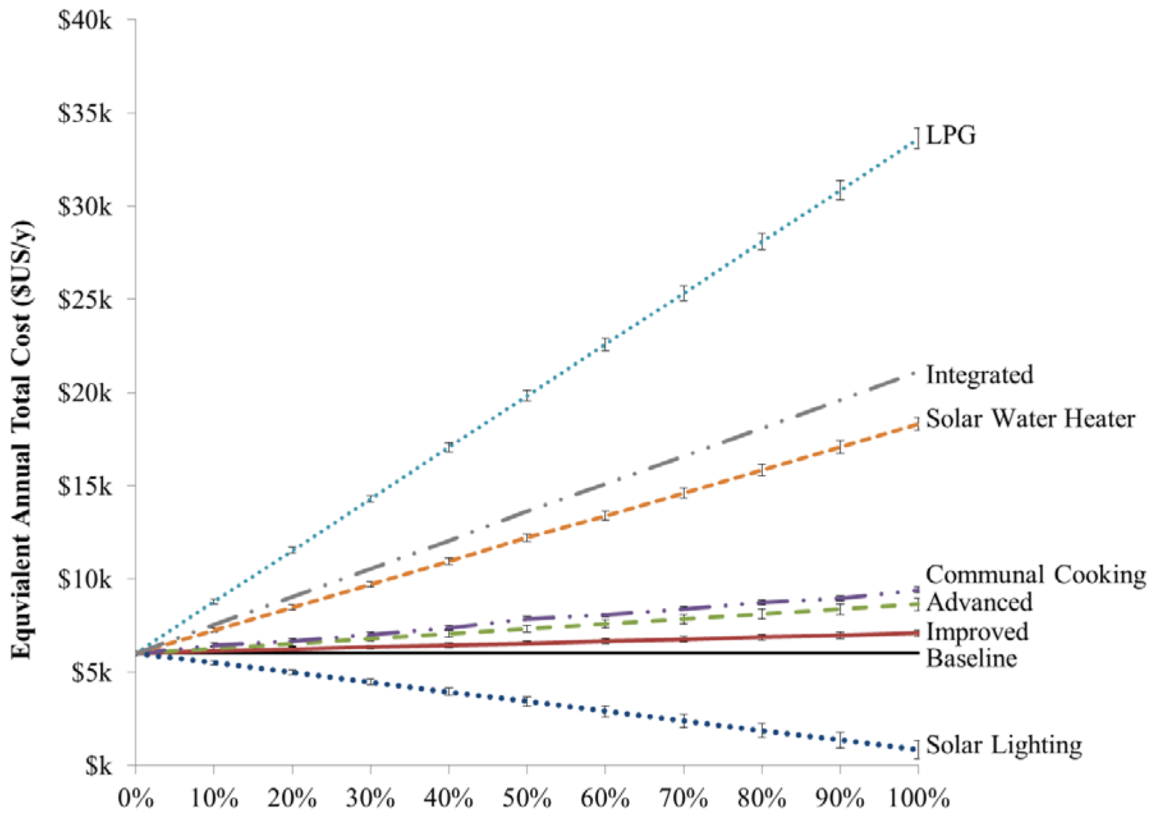

Figure 5.11 Equivalent annual cost (SUS/y) including the opportunity cost of time as a function of displacement fraction, 95% confidence interval

5.4.5 Quality of life

The overall quality of life metric is especially important because a higher quality of life offered by a technology indicates a greater likelihood of voluntary adoption by members of the community, and therefore a higher displacement fraction. The improved cookstove and communal cookstove strategies provide a slight net decrease in quality of life because they are less convenient and require a change in cooking practice. In the case of the advanced cookstove, these factors are slightly outweighed by assumed increases in desirability and safety offered by modern highly-engineered cookstove designs. Although there is no doubt

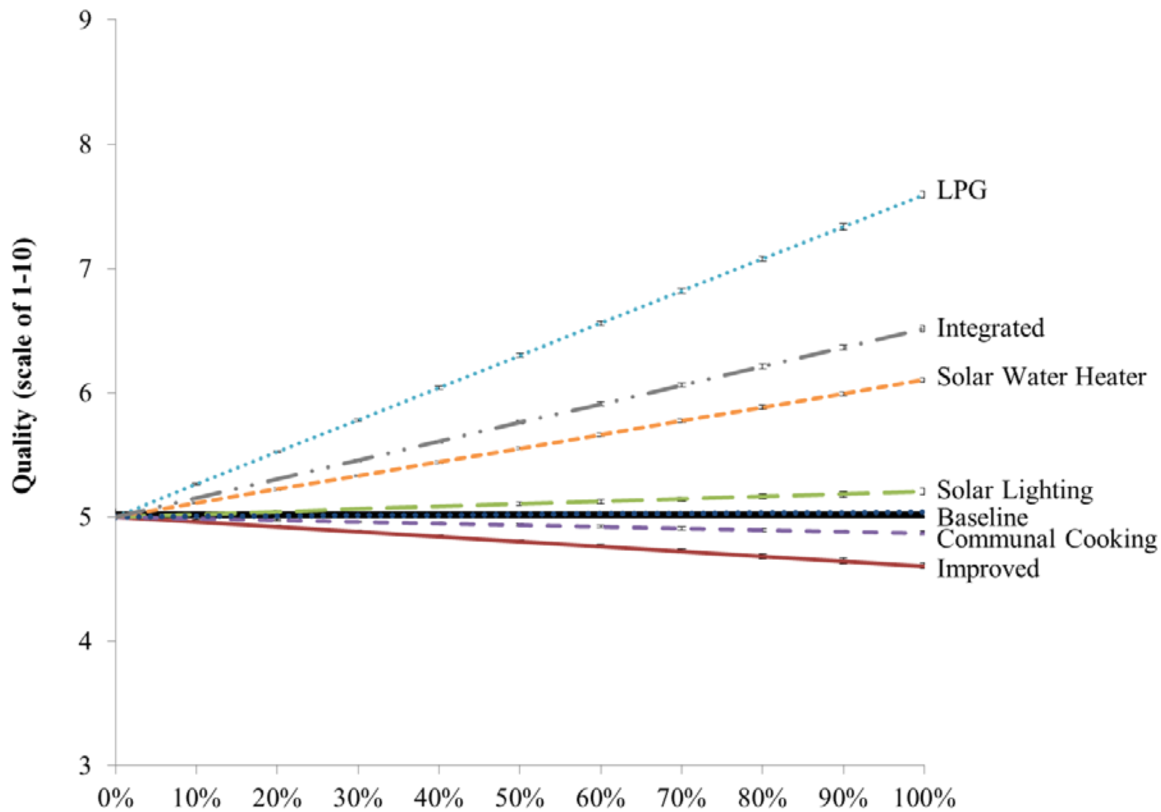

Figure 5.12 Quality as a function of displacement fraction, 95% confidence interval

that lighting offers a dramatic increase in quality of life to a family by extending their day and allowing for educational activities, the model algorithm calculates impact as a weighted average by energy use which is minimal in the case of lighting. This issue should be investigated to determine a weighting method that more appropriately reflects this. The key message of this metric, however, is how the solar water heater and LPG (and solar lighting given a different weighting algorithm) strategies clearly offer significant improvements in all respects, illustrating the importance of offering technologies that provide a distinct and recognizable improvement in quality of life to the user. This analysis is supported by the evidence from the field, which shows the natural inclination of users is to adopt modern and convenient fuels and devices such as these as income allows. While presently these metrics are based on the belief and experiences of the author, a user-driven system of categorization, weighting, and ranking in the future will further increase the utility of this quality of life metric.

5.5 Summary

In order to consolidate the analysis presented in the previous sections, Figure 5.13 shows the overall comparison of all strategies in terms of all outcomes simultaneously. The pentagram at zero represents the baseline scenario, -1 at the center represents the least desirable outcome, and the largest pentagram the most desirable outcome.

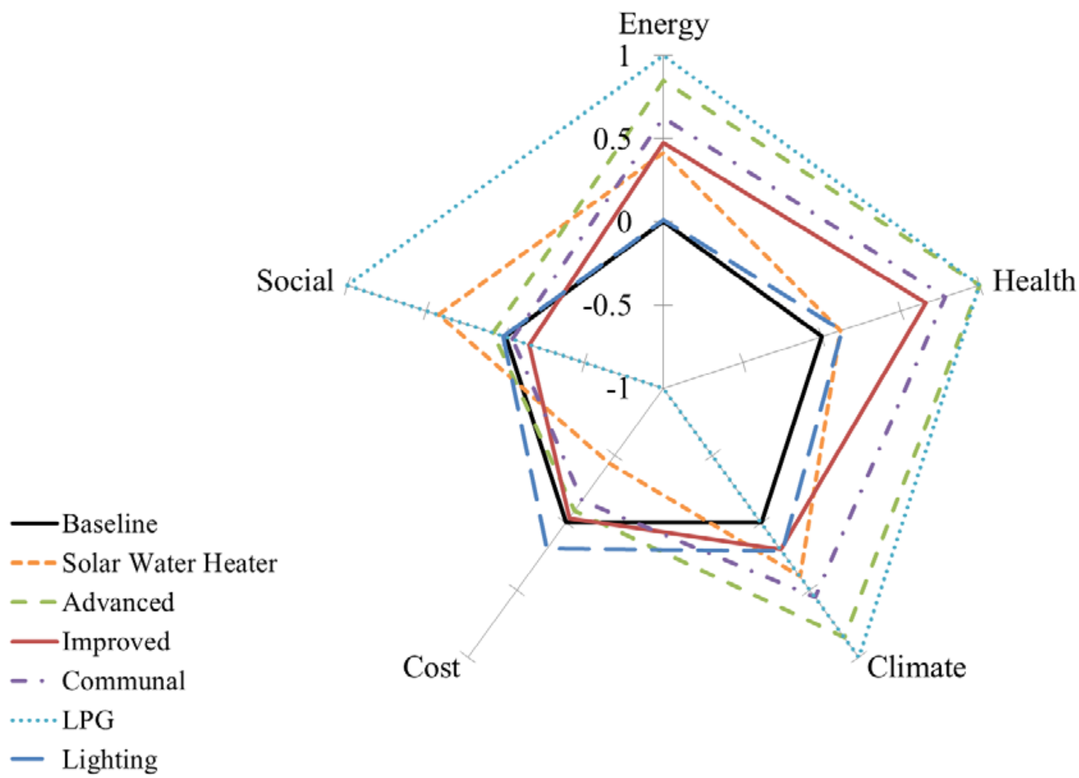

Figure 5.13 Graphical comparison of the relative outcomes for six potential strategies at 100% displacement in terms of five major objectives

The figure shows that all strategies can offer an improvement on health, climate, and energy consumption. Most of these cost equivalently more each year than the baseline when accounting for fuel, time, and purchase costs although the lighting actually represents a financial gain. Due to the conflicting and varying outcomes amongst objectives, no single strategy is a clear winner, making the decision difficult.

Table 5.4 shows a comparison between the overall outcomes of the optimal integrated strategy and a modest but affordable strategy implementing improved cookstoves. These data include contributions from space heating and lost multifunction when switching away from the three-stone fire for cooking. The improved strategy results in the lowest estimated annual cost (EAC) to purchase and maintain devices and offers an impact lasting as long as the lifetime of the cookstove, or two years. Assuming 100% adoption, this strategy results in a net benefit of roughly 1,000 GJ/y energy savings, 70 metric tons CO_{2e} savings, 40,000 m^3/y reduction in RHI, a modest operating cost savings of $300/year, and a slight reduction in quality of life of -0.4 due to lower convenience and a required disruption in current practice. If users were to bear the cost to purchase and maintain the cookstoves, the cost would appear to be about $1,600 per year across the village. If donated by implementers, this value would be closer to $1,000 due to a lower time value of money. It is likely this adoption fraction will be significantly lower than 100%, however, due to the limited improvement in quality of life, small savings in operating cost for the village, and limited lifetime/durability of the cookstoves. This has been observed in the field as limited lasting success of this strategy over the past several decades.

Table 5.4 Analysis of feasibility and net benefits relative to baseline: single device versus integrated approach

	Technology Strategy						Summary	
	Improved	Advanced	Communal	LPG	SWH	Lighting	Imp-roved	Inte-grated
PRIMARY ENERGY SAVINGS (GJ/y)								
General Cooking	743	1,291	1,542	1,508	0	0		
Specialty Cooking	95	182	0	216	0	0		
Water Heating	319	558	0	652	952	0		
Lighting	-33	-33	-33	-33	0	34		
	1,157	1,291	1,542	216	952	34	1,091	2,437
CLIMATE SAVINGS (tCO2e/y)								
General Cooking	96	246	282	279	0	0		
Specialty Cooking	11	35	0	40	0	0		
Water Heating	41	107	0	121	143	0		
Lighting	-74	-74	-74	-74	0	77		
	149	246	282	40	143	77	71	500
HEALTH SAVINGS (RHI as m3/y)								
General Cooking	52	75	77	76	0	0		
Specialty Cooking	3	5	0	6	0	0		
Water Heating	6	8	0	8	8	0		
Lighting	-9	-9	-9	-9	0	9		
	61	75	77	6	8	9	47	89
OPERATING COST SAVINGS ($US/y)								
General Cooking	871	1,495	1,787	-14,881	0	0		
Specialty Cooking	55	155	0	-2,461	0	0		
Water Heating	373	645	0	-6,434	1,103	0		
Lighting	-832	-832	-832	-832	0	864		
	1,300	1,495	1,787	-2,461	1,103	864	428	933
QUALITY OF LIFE IMPROVEMENT								
General Cooking	-0.5	0.3	-0.2	3.2	0.0	0.0		
Specialty Cooking	-0.5	0.3	0.0	3.2	0.0	0.0		
Water Heating	-0.5	0.3	0.0	3.2	5.0	0.0		
Lighting	0.0	0.0	0.0	0.0	0.0	4.5		
	-1.5	0.3	-0.2	3.2	5.0	4.5	-0.4	1.5
Device Cost r=50%($US/y)	1,638	4,085	5,596	3,069	13,534	4,001	1,638	24,132
Device Cost r=5% ($US/y)	1,116	2,728	1,975	957	3,179	3,422	1,116	9,729

The integrated strategy includes the use of a long-lasting solar water heaters for heating water, LPG for specialty cooking, and advanced cookstoves for cooking. Relative to improved cookstoves alone, energy savings are increased 1.5 times, the reduction in greenhouse gases is increased 7 fold, health impacts reduction doubled, and quality of life transitioned from a decline to a significant improvement. The reduction in operating cost also tripled, offering significant benefit to the user. However, the devices are expensive at an estimated annual cost to the user of approximately $24,000/y assuming a user discount rate of 50%. If donations, subsidies or financing were available to provide these devices at a discount rate of 5%, the total capital cost is brought down to approximately $10,000. In that case it would cost about $12 per person per year to provide the entire village with all of the physical devices needed to optimally meet their energy needs while simultaneously providing the user a savings in operating cost. This does not include overhead and costs of implementation, however; even if these expenses were twice that of the device capital costs, it would potentially cost $25-$35 per person per year to provide these comprehensive energy services. This would equate to roughly $30 million to provide all 1 million of the rural population of Mali with the devices required to meet their energy needs more effectively. For comparison, the external funding needed to implement systematic interventions for health, agriculture, and education in the Millennium Villages was estimated at $110 per villager per year, which is reportedly consistent with commitments made by the G8 countries in 2005 (Millennium Project, 2015). Therefore, $12-$35 per person worth of investment to provide for optimum and sustainable energy services is a relatively low figure. An integrated strategy such as this is also in line with the thinking of Jeffrey Sachs (2005) and the Millennium Villages that poverty cannot be alleviated with a disparate and piece-meal approach, but only a comprehensive strategy that meets all needs simultaneously can help families to escape the "trap" of poverty.

The benefit of an integrated strategy is that high proportions of adoption rates would be expected, as this strategy in many respects represents the natural progression of fuel and device stacking, which occurs as income allows. For example, it has been repeatedly shown that consumers convert to LPG for small tasks and install solar water heaters despite continuing to cook on their traditional cookstoves (Masera, Staatkamp, and Kammen, 2000). An integrated strategy reduces pressures on forests, improves health and climate, increases convenience and quality of life for the user, and the additional cost of LPG is offset by the savings in wood fuel and kerosene. Because this strategy follows natural tendencies and offers an improvement in quality of life, no additional incentives are needed other than ensuring market availability and affordability of the technologies.

CHAPTER 6

THE IMPACT OF APPLICATION FACTORS ON THE OUTCOME OF HOUSEHOLD ENERGY TECHNOLOGIES

The potential impacts a technology may have when placed in service are dependent on how the technology is applied within a community. This application will differ based on the energy needs and fuel supply in that community, as well as the variability expected from both testing and use. These differences in application are important to understanding and predicting system-level outcomes in order to choose appropriate strategies.

6.1 Energy Needs

Energy needs differ across communities due to demographic, cultural, and geographic conditions. Investigation of impacts of energy strategies on villages with different energy needs fractions from published studies indicates how costs and benefits for various outcomes change at the village scale. As shown in Figure 6.1, in the average of the villages in India reported by Astra and Reddy (1981), the improved cookstoves have a potential to make a significant impact, even more so than in the Malian village shown in Figure 5.2. Note that specialized tasks were not disaggregated from the cooking process in that study, however. In the villages in India, improved cookstoves can reduce energy consumption by about one-third, climate impacts by about one-half, and operating cost and health impacts by nearly two-thirds.

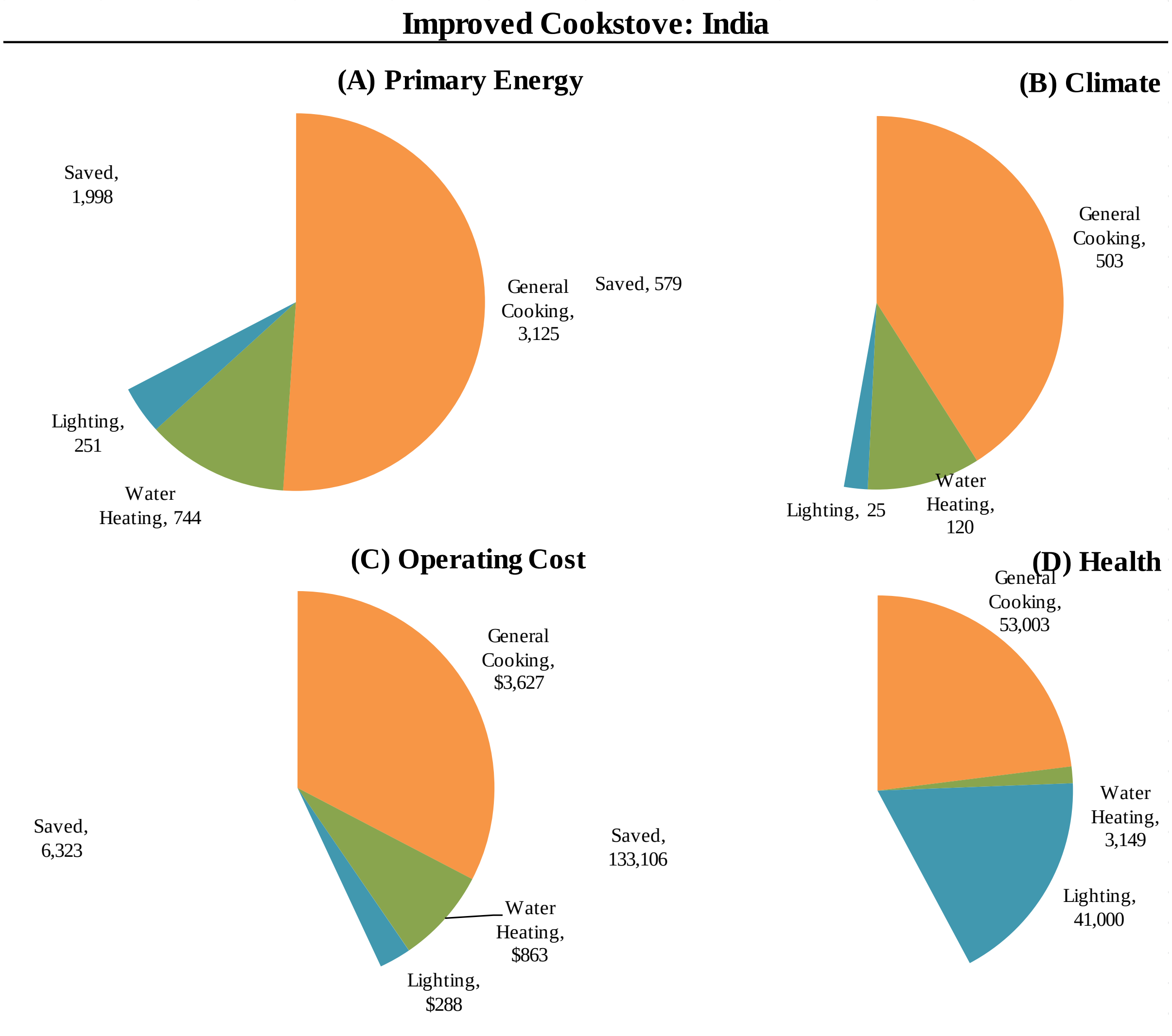

Figure 6.1 Analysis of the improved cookstoves strategy in India in terms of (A) Primary energy consumption (GJ/y), (B) Climate impact (tCO2e/y), (C) Operating cost ($US/y) including fuel purchase and collection time, and (D) Health impact (1000*RHI/y)

However, in the community in Cambodia studied by San (2012), the impacts of improved cookstoves are less substantial (Figure 6.2). In the Cambodia community, specialized tasks include preparing food for animals and protecting animals from insects. The former likely requires a large cooking vessel and the latter is intended to produce smoke, so an improved stove would not be appropriate, and those tasks are therefore assigned to the baseline. As a result, energy, climate, and cost savings are less than 25%. Perhaps in this particular community, rather than focusing on cookstoves at all, an electric "bug zapper" running off a solar-charged battery might make a significant impact in terms of all outcomes (except human health) since animal protection is responsible for 22% of the energy use.

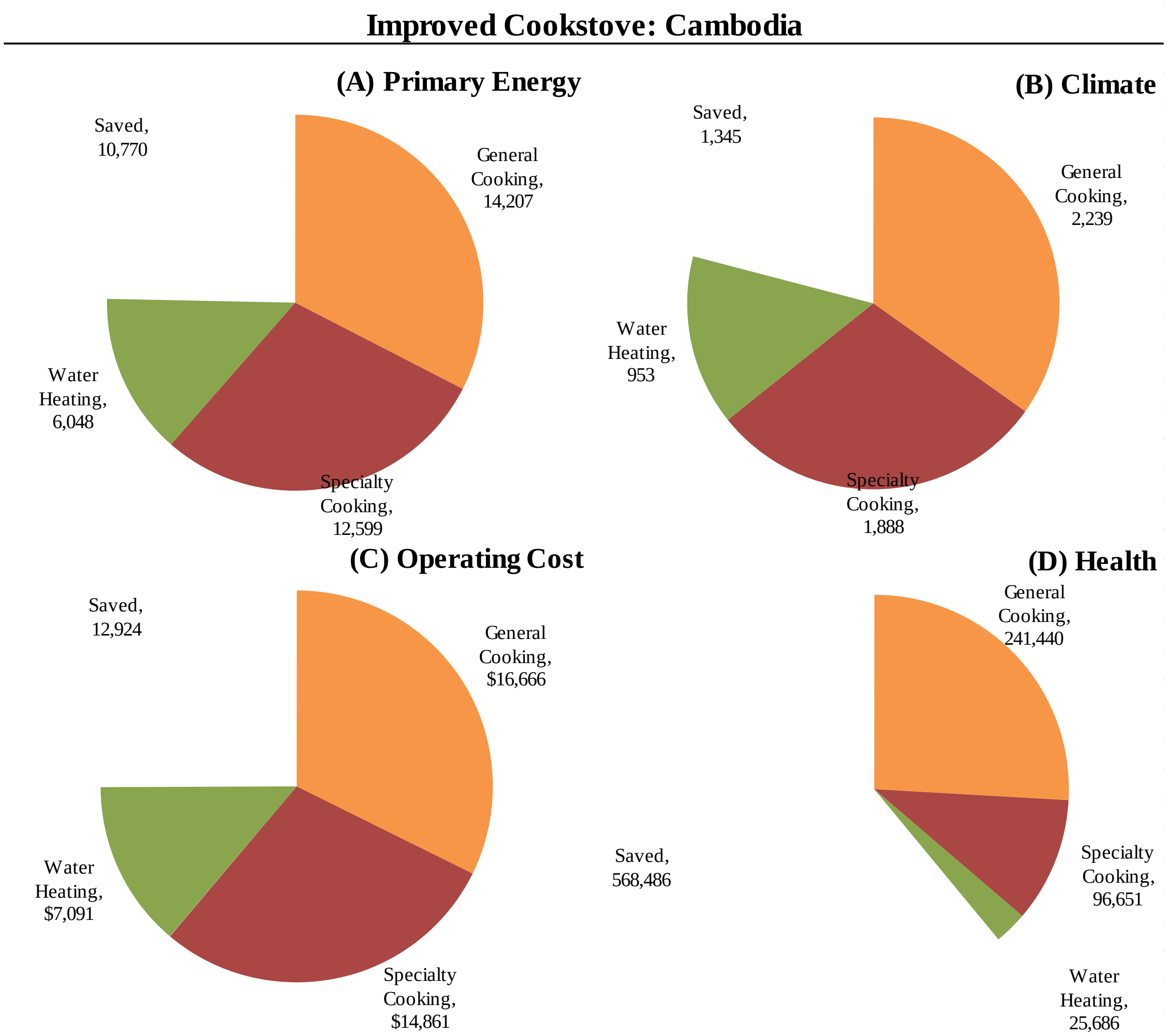

Figure 6.2 Analysis of the improved cookstoves strategy in Cambodia terms of (A) Primary energy consumption (GJ/y), (B) Climate impact (tCO2e/y), (C) Operating cost ($US/y) including fuel purchase and collection time, and (D) Health impact (1000*RHI/y)

Due to differing fractions of energy use in communities across the globe, it is likely that the strategy that will make the most impact will vary widely. Therefore, the systems approach presented in Chapter 2 is needed to identify the strategies and devices that are best suited to a given community.

6.2 Fuel Supply

In the example Malian village, it presently takes an average of 9.3 hours to collect 1 GJ of fuelwood because women and children travel roughly 3-8 km per trip to fetch the fuelwood (Johnson and Bryden, 2012a). They do not use tools to cut growing trees but rather gather fallen limbs and branches, suggesting a sustainable harvest in this case. If the region was to become more fuelwood stressed and this time increased, the optimal strategy may change when the impact of the value of time is considered, shown in Figure 6.3. Use of improved cookstoves or pot shields for all tasks remains the least costly option if used at 100% displacement for the current fuel collection time. If the fuel collection time were to nearly double in this or a different community, the higher-efficiency advanced stove would become more cost effective. The gasifier stove (assumed to have the same purchase price as an improved stove) uses prepared fuel, which is assumed to require 10% more time to process in addition to harvesting. However, if prepared fuel pellets or briquettes were produced using waste products such as crop residues or roots that are available closer to home, the collection time would decrease, further making that type of cookstove even more attractive. This supports observations from the field about user valuation of fuel savings.

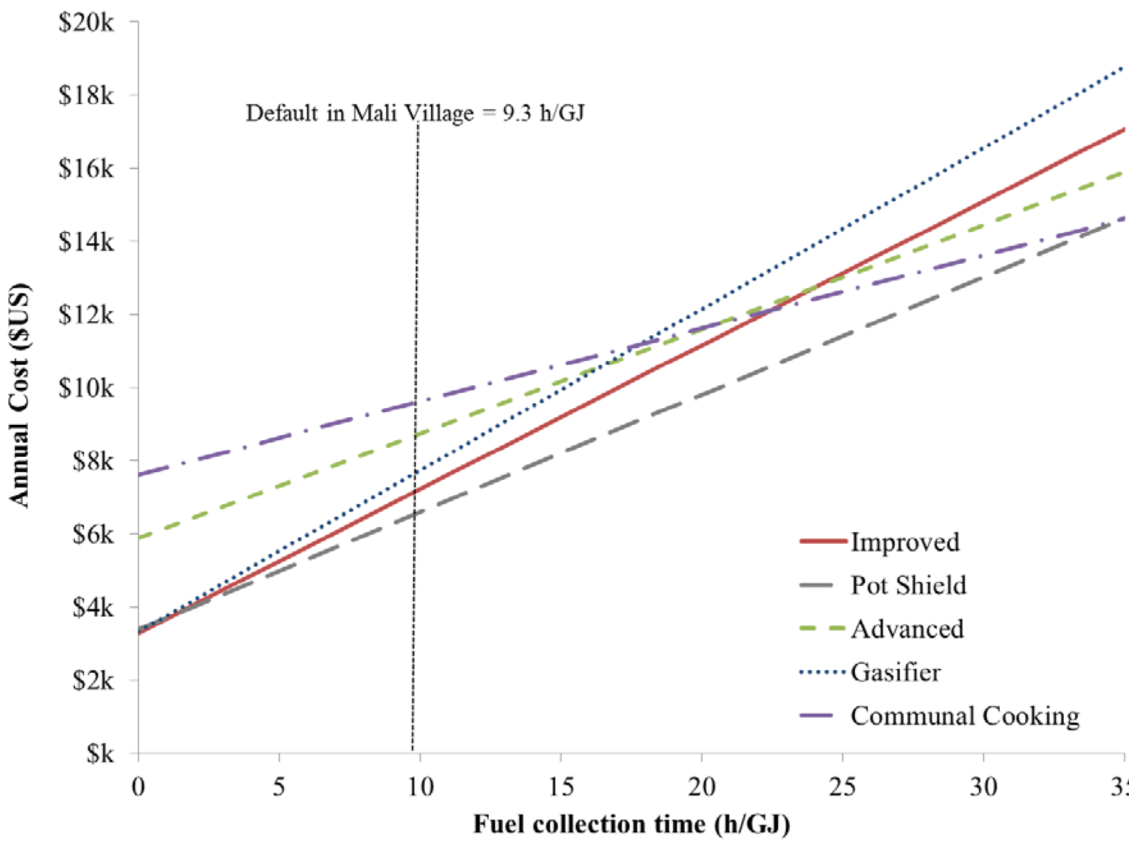

Figure 6.3 Annual cost ($US) as a function of fuel collection time (h/GJ) for several types of cookstoves

Another aspect of the fuel supply is moisture content. Often cookstove designs operate optimally only with dry fuel, which simply may not be available in the field. Particularly with advanced cookstoves, the performance is designated in the laboratory with kiln-dried fuel and performance may be severely affected with fuel more typical of the field. Therefore, the performance of the cookstove when burning fuel at a moisture content level seen in the community should be measured and applied to the analysis for the fraction of the year that fuel with a high moisture content would be used. For example, Jetter et al. (2012) found that the emission rate of CO from a natural draft gasifier stove more than doubled when wet fuel was used in relation to dry fuel. Changes of this magnitude will likely influence the optimal strategy choice. More data on the performance of cookstoves at moisture levels representative of the field is needed for analysis in the model. In this way a more accurate comparison to other options may be available, or it would encourage the design of cookstoves that more effectively burn the fuels typically found in communities.

6.3 Performance Variability

Performance variability and uncertainty and their implications on outcomes are important to understanding whether strategies are statistically separable. Many figures in the previous discussion showed the 95% confidence intervals of the impacts given the reported performance variability anticipated from stove testing, some as high as 122% of the mean, or assumed as 25% of the mean if no variability was reported. In the preceding analyses for generalized stove and device types, most strategies were statistically separable. However, when choosing between two similar designs, the overall impacts in the village may not be separable. Figure 6.4 shows the impact of variability on statistical separability of primary energy use per year for an improved stove at both 30% efficiency and 40% efficiency. The variability begins at 0% and increases up to 50% relative to the mean. The chart shows that beginning at a standard deviation at about 33% of the mean, the solutions may become inseparable statistically when all other variability in the village is accounted for. For cookstoves that are closer together in measured efficiency, an even smaller variability in efficiency performance would be required to choose between two strategies with any certainty. The figure also shows that as variability increases, the Monte Carlo simulation becomes less stable and will require more than 1,000 iterations to converge.

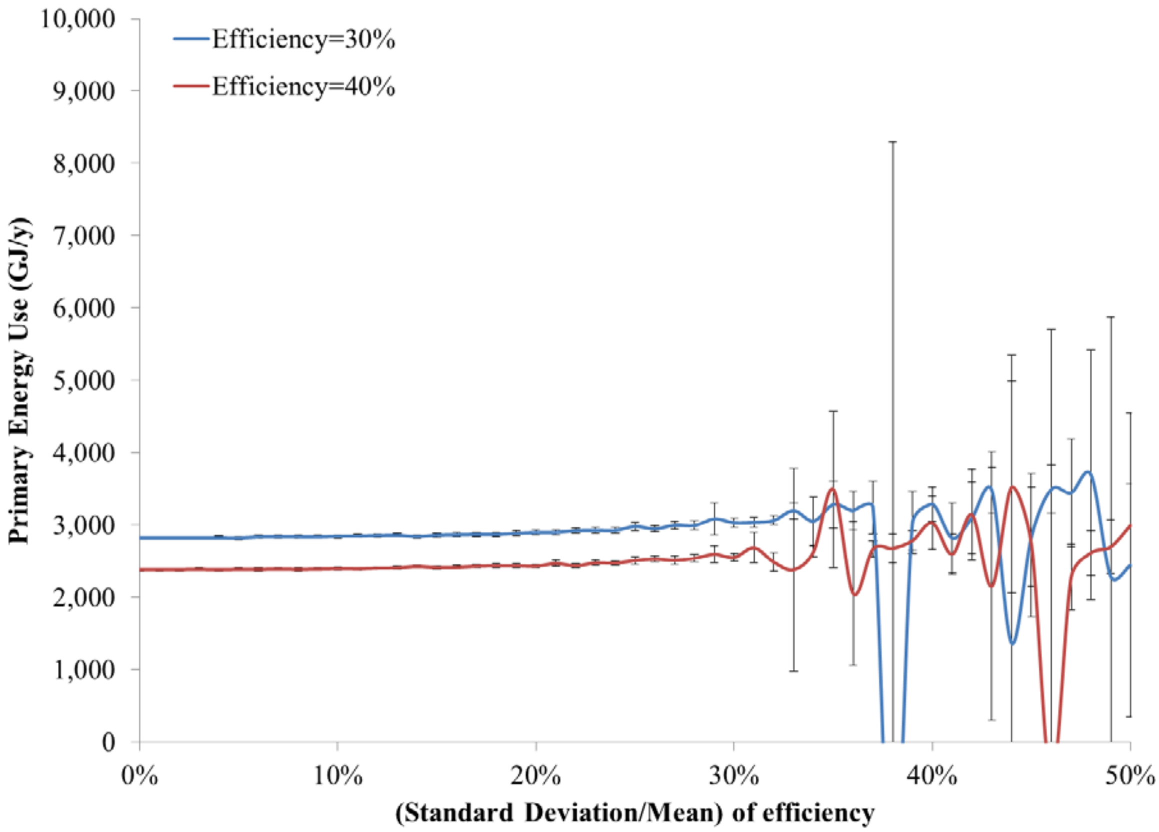

Figure 6.4 Energy use variability for improved cookstoves at 30% and 40% efficiency as a function of the ratio of deviation to mean, shown with 95% confidence intervals

Due to the inherent variability of combustion and operational processes, this indicates that small changes in precision laboratory testing of the performance of iterations of cookstove designs is unlikely to translate to statistically separable differences when that device is placed within the village energy system. Therefore, it is unlikely that the development of precision laboratory testing procedures will change the outcomes of the devices when placed in service. To better understand the sources and contributions of uncertainty from the technology performance and from local energy needs and variables, an uncertainty analysis can be performed.

This chapter showed the importance of considering application during the selection process for energy technology strategies. Due to differing energy needs and end uses in communities across the globe, it is likely that the strategy that will make the most impact will vary. Therefore, the systems approach presented in Chapter 2 is needed to identify the strategies and devices that are best suited to a given community. In addition, the time spent gathering fuel is directly linked to the valuation of fuel savings offered by a technology. As a result, more expensive/efficient devices may be more suited in communities where fuel supply is limited and requires more time to procure. The moisture content of a local fuel also dictates the device that will be most appropriate depending on its ability to operate with a range of fuel moisture levels, as does fuel harvest renewability dictate climate impacts. Finally, precision testing in a laboratory setting is unlikely to translate to statistically separable differences when placed within the village energy system.

CHAPTER 7

THE IMPACT OF TECHNOLOGY DESIGN CHOICES ON OUTCOMES IN THE HOUSEHOLD ENERGY SYSTEM

The design process for an energy technology includes a number of choices and trade-offs to be made regarding capability, performance, cost, and lifetime. These characteristics can often be manipulated to meet the objectives for a given community. This chapter examines the impacts of design choices including usability, multi-functionality, efficiency, emissions, cost, and durability on the outcomes of various strategies. Attention to these details allows for an approach to design of technologies with the intended outcomes in mind.

7.1 Usability

As discussed in Chapter 2, usability is defined as a device's ability to effectively, efficiently, and satisfactorily perform a task in terms of the 5 E's. The effectiveness with which the traditional three-stone fire conducts an array of energy tasks is high due to the wide range of acceptable fuel types, loading styles, tending frequencies, and pot sizes that can adapt to meet the needs of the user. In contrast, cookstoves are often designed to operate optimally within a narrow range of each of these factors. As a result, many cookstove designs are not effective and usable for more than one or two tasks in the household, and therefore, the tasks to which they are applied is limited. Figure 7.1 shows the savings offered by several stove types for each task (cooking, water heating, etc.) for comparison of impacts on a task-by-task usability basis.

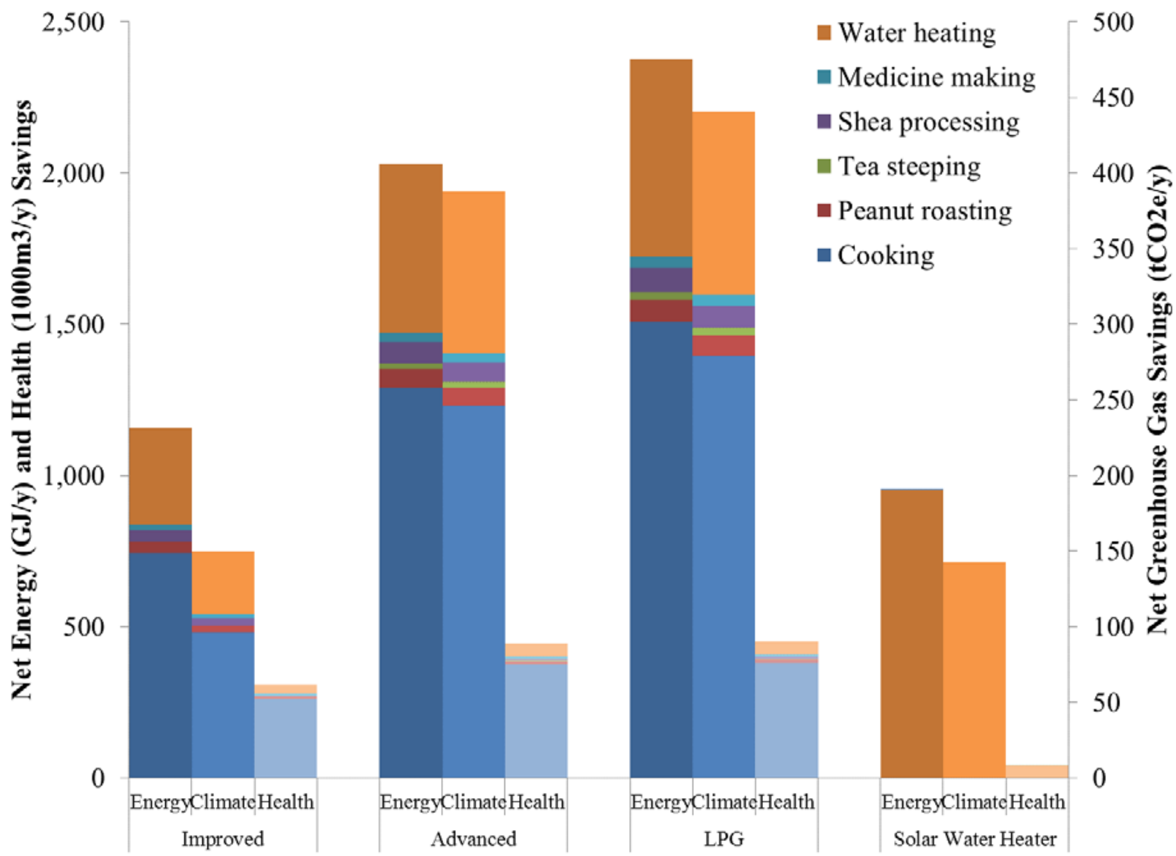

Figure 7.1 Relative contributions of tasks to potential annual energy, climate, and health savings

In many cultures water heating is often done outdoors in large pots with a minimally tended fire. It is unlikely the user will be willing to heat water in ways that require more tending or smaller pots. Therefore, an advanced cookstove that requires frequent tending and/or cannot accommodate larger pots will not be useable for this significant fraction of energy consumption. Similarly, the specified pot and range of firepower, as well as the degree of tending required, for an advanced stove might mean that it is not useful for the long slow simmering required for making medicine, or the hot roasting of peanuts in a wide shallow pan. Therefore, if the savings from specialty cooking and water heating by the advanced stove are removed, there may no longer be a statistically separable improvement over an improved stove in terms of energy or health. Therefore, the effectiveness of a stove design for the variety of tasks needed should be considered in projections of expected impacts. So devices should be designed with an approach that either (1) can be used effectively for as many tasks as possible, or (2) are specially designed to optimally perform the tasks which represent the largest potential impact. These details will have a larger influence on outcomes than small changes in efficiency or emissions.

A successful example of the second strategy was developed by HELPS International in Guatemala. In order to reduce the health impacts and safety concerns of the three-stone fire, they worked to implement built-in-place stoves equipped with a chimney and griddle for frying tortillas called the ONIL Plancha Stove. However, they found that the stove was not suited to the weekly cooking of a large pot of nixtamal, the flour meal used to make tortillas. Therefore, they designed a large-capacity Nixtamal Stove to optimally address this need as well (Helps, 2015).

7.2 Multi-functionality

The multifunctional nature of the three-stone fire is significant in a household, so much that even when a new device is adopted for certain tasks, energy use may not change because the three-stone fire use is continued for secondary purposes such as lighting and heating (Bilecki and Wingenbach, 2014; Howells et al., 2005). When improved stoves or practices reduce the ambient light or heat output of the cooking process, these missing services are made up for elsewhere and represent additional energy and expense as well as a reduction in the net impact on health and climate. In the analyses presented throughout this dissertation, all village-scale results of energy use, climate impacts, and costs account for this multifunction, and if missing from the cooking device being analyzed is instead added to the space heating and lighting requirements according to the assumptions.

The multifunctional nature of the three-stone fire provides an estimated 45,000 hours of lighting at an albeit low level in the village each year assuming one hour per day of light is provided during evening cooking in the household of each of the approximately 123 cooks operating three-stone fires each day. It is assumed that kerosene lanterns are used only when the cooking fire is not providing light. Without the ambient lighting from the three-stone fire and if it was 100% displaced by another technology, the present annual kerosene use (assuming no electric lighting available) would need to increase by 900 liters (32 GJ) of kerosene at a cost of approximately $800 in order to provide the same hours of lighting service. The cost of this additional kerosene is approximately $6.50 per household per year simply to maintain the estimated current level of lighting offered by the three-stone fire for one hour each day. For a household this effectively increases the cost by 50% to purchase an improved cookstove costing ~$15 that does not simultaneously provide sufficient lighting.

Similarly, the heating provided by cooking with the three-stone fire is equivalent to an estimated 79 GJ of heat in the evening each year. This assumes the waste heat from indoor cooking is equal to one minus the thermal cooking efficiency and is valued during one-fourth of the year during the cold and dry season and one-sixth of the daily cooking time, which is in the evening hours. Therefore, this lost heat is added to the 814 GJ required by a heating device in cases when the space heating service during cooking is reduced due to stoves with improved efficiency or chimneys.

For comparison, Table 7.1 shows the savings in cooking and water heating processes offered by the improved, advanced, and LPG scenarios relative to the added requirements for lighting and heating due to the lost multifunction when switching away from the three-stone fire. It shows that the lost lighting leads to a 1%-3% reduction in energy savings, 16%-47% in climate, and 9%-13% reduction in health savings paired with a 35%-60% reduction in cost savings due to the cost of kerosene for lanterns. For heating, the fraction of energy, cost and climate savings lost represent 3% or less, and the health savings are more on the order of 8%-11% due to the enclosed indoor nature of space heating.

Table 7.1 Additional lighting and heating requrements when switching away from the three-stone fire for cooking due to multi-functionality

	Energy		Climate		Health		Cost	
	Savings (GJ/y)	% of Savings	Savings (tCO_{2e}/y)	% of Savings	Savings (m^3/y)	% of Savings	Savings ($US/y)	% of Savings
Improved cookstove	1,157		149		61,008		$1,300	
Extra Lighting Required	33	3%	74	50%	8,835	14%	$832	64%
Extra Heating Required	33	3%	3	2%	5,181	8%	$39	3%
Advanced cookstove	2,031		388		88,724		$2,294	
Extra Lighting Required	33	2%	74	19%	8,835	10%	$832	36%
Extra Heating Required	57	3%	6	1%	8,805	10%	$66	3%
LPG	2,376		441		90,066		-$23,776	
Extra Lighting Required	33	1%	74	17%	8,835	10%	$832	
Extra Heating Required	63	3%	6	1%	9,848	11%	$74	

Assumes cooking with the three-stone fire provides 1 hour of lighting each day and 4% of TSF cooking energy is appreciated for heating, and 100% displacement of alternative technologies

The figures in Table 7.1 are tightly coupled to the coarse assumptions regarding the quantity and timing of valued heat and light. Also in different communities it is likely the assumptions for the quantity of heating and lighting desired throughout the day are different. In this Malian village near the equator and the Sahara desert, heating and lighting are not as essential as in a community in the Himalayas of Nepal in the winter, for example. Yet even in this community requiring minimal lighting and heating relative to other regions, the impact of the multi-functionality of the three-stone fire is significant. The analysis also indicates that the lighting services offered by the three-stone fire may be highly valued by off-grid users who would otherwise have to purchase kerosene, using the little monetary income available. As a result, cookstove designs that offer simultaneous lighting and heating levels similar to that of the three-stone fire are more likely to be adopted by the user and displace the use of the three-stone fire in the evenings. Otherwise, there is a good chance that the use of more polluting traditional devices may continue in addition to the new cookstove.

A second aspect of multifunction that has been the subject of recent development is the addition of a thermoelectric generator with a Peltier element to a cooking stove in order to utilize the heat gradient from the interior to the exterior to produce a small amount of electricity (Mastbergen, 2008; BioLite, 2015). This electricity could be used to power a small light or charge a cell phone, for example. This would be a good utilization of waste heat when the cookstove is already in operation. However, given the suppressed demand for electricity services, it is possible the device would be run continuously simply for the electrical service, with a relatively very low electrical generation efficiency and high level of emissions. Analysis is needed to determine whether the power produced during normal cooking tasks would be sufficient or whether users might burn additional fuelwood beyond what is needed for cooking to produce more electrical power. In this case very polluting and inefficient power production would occur relative to other options such as solar panels for power production. Therefore, the system-level impacts of these scenarios should be compared. This analysis is possible with this model but is reserved for a later time when field data are available.

7.3 Thermal Efficiency

The use of fuelwood is frequently cited as a source of drudgery and deforestation in communities. As a result, reduced fuel use is almost always a primary goal of household energy strategies. Increasing thermal efficiency is the most common method of achieving this. Efficiency of almost any device can also be increased by simple changes in practice such as the use of a tight-fitting lid on the pot, using burning embers to ignite the fire, or the use of a pot shield, or “skirt”. Johnson (2012) estimated the use of burning embers to ignite fires has the potential to save 10% of energy, and a general rule of thumb states that a pot shield can reduce fuel use by 25%, as shown by data in (MacCarty and Bryden, 2015). There are also design techniques for increasing thermal efficiency of technologies, including reducing losses through insulation and increasing the heat transfer coefficients to the working media. Finally, the use of energy sources other than fuelwood has the potential for the greatest reduction in fuel harvest requirements.

Figure 7.2 shows the forest harvest rate in metric tons per year for several strategy scenarios. The impact of the solar water heater and the improved stove are not statistically separable at 95% confidence, suggesting programs to slow deforestation could focus on either strategy with similar results. The advanced cookstove performance level offers at least 45% thermal efficiency according to the ISO (2012) definition and may reduce the harvest considerably. However, when usability issues as discussed previously are considered and if that stove is used only for cooking tasks, the impact is reduced to just barely statistically separable from that of the general improved cookstove and less than that of an improved stove with a pot shield. The use of pot shields with an improved cookstove reduces the forest harvest approximately 20% overall compared to the improved stove alone if used for all tasks. But they are also limited by pot size, so will likely not be easily used for all tasks. In addition, pot shields are cumbersome to use and a known safety hazard because they make the pot difficult to place on and off the stove, are made of hot bare metal, and are often sharp.

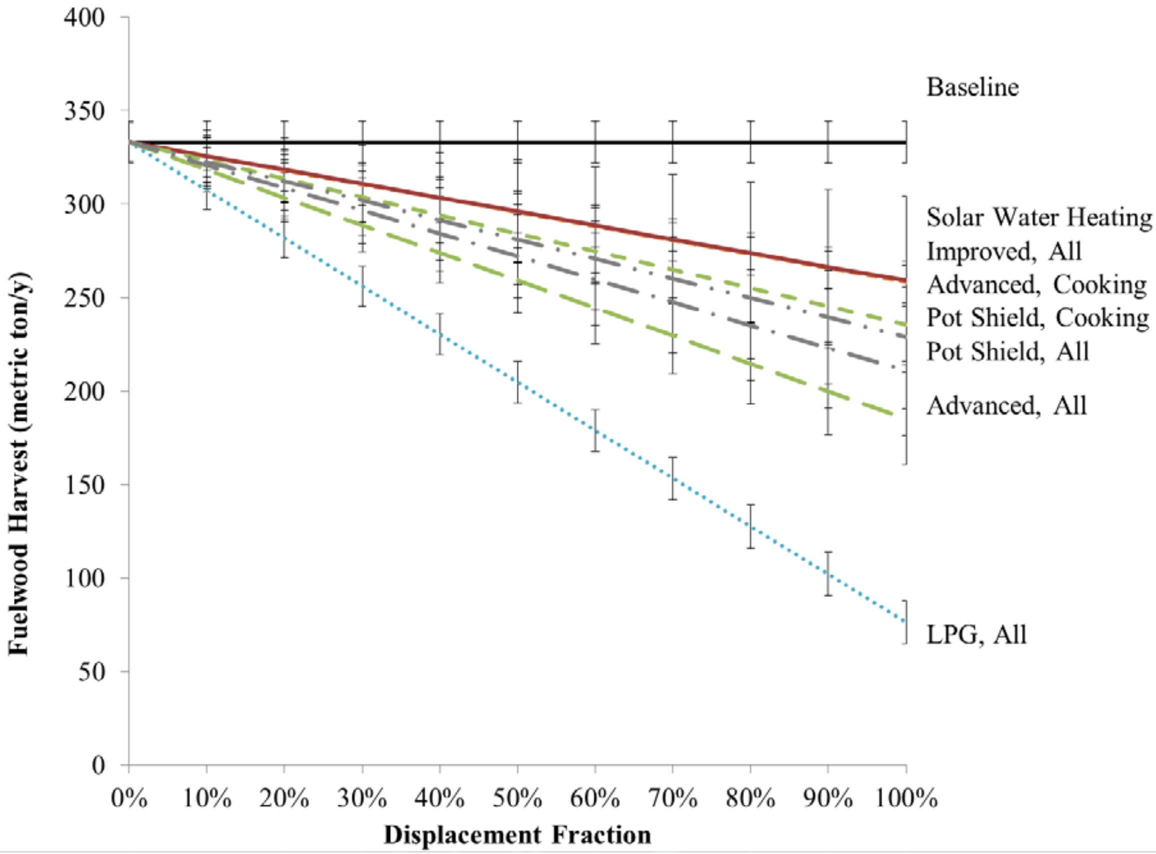

Figure 7.2 Forest harvest rate for various scenarios, 95% confidence interval

Although the solar water heater, improved stove, and advanced stove for cooking have relatively equal impacts on forest harvest rate, it is likely the solar water heater may enjoy greater adoption (but may potentially suffer reduced capacity during the rainy seasons) than the advanced or improved cookstoves, which does not offer as significant of an improvement in quality of life as the solar water heater. The optimal strategy in this case is not clear. Naturally devices that do not use fuelwood at all have the greatest potential to reduce forest harvest rate.

Exploration of alternate fuels such as biogas or crop residue briquettes would be an effective strategy to slow deforestation in areas with a sufficient feedstock. In the Malian village, Johnson (2012) estimated a suitable biogas feedstock to displace 14% of the wood used for domestic cooking needs. So in conclusion, the most substantial reductions in fuel harvest rate are not likely to be achieved through incremental improvements in the thermal efficiency of existing devices, but in the adoption and use of devices that do not use fuelwood at all.

7.4 Emissions

Emissions are a concern in two areas: the total emissions produced impacting climate and the indoor air concentration of emissions, which influences health. Climate is impacted by reducing fuel use or cleaning up combustion, and health is impacted by reducing fuel use, cleaning up combustion or through use of a chimney. In order to address concerns for both health and climate, recent advanced biomass stoves have been designed to meet strict emissions limits that seek to minimize greenhouse gases and aerosols and maintain air quality at levels deemed adequate by WHO (WHO, 2014). These target emission levels must approach that of LPG to meet these requirements. Techniques for reducing emissions besides simply reducing the fuel consumed include reduced firepower, optimized pots and channel gaps, batch feeding in semi-gasification-type stoves, and metered fuel in forced drafts stoves (Still, Bentson and Li, 2014). Although these techniques can reduce emissions, they also narrow the applications and limit the tasks that can be conducted. For example, a stove with a pot optimized for the volume needed for typical cooking will not be suited for heating water or roasting peanuts. Nor will a frequently fed forced draft stove be useful for making medicine by simmering unattended for a long period of time. Thus either these tasks will continue to be conducted with the baseline device or the user will need to change their practices to adapt.

Figure 7.3 shows the simulated effects of the stove type on health impacts reported as the relative hazard index in cubic meters of air required to reduce emissions to safe levels. This figure illustrates why there is so much attention paid to very clean-burning advanced stoves; it is because the strict emissions requirements result in health impacts statistically inseparable to that of LPG cookstoves. However, again if usability is limited, the impacts are reduced. The health impact of an improved stove is a little over half of that of the advanced or LPG used at full displacement. Between the possible health impacts of improved and advanced stoves, however, are the stove with a chimney and the option of communal cooking. The first of these does not save fuel but removes the emissions from the kitchen, protecting health. The second saves fuel by economies of scale in larger cooking volumes as well as being equipped with a chimney. The health impact of a solar water heater, however, is minimal since heating water typically occurs outdoors and ventilation is accounted for in the model. In this case, the health impacts of all types of cookstoves lie within a relatively narrow range and are therefore highly dependent on the adoption and usability of the stove. In fact, as was seen in Chapter 5, the most significant impact on health would be made by displacement of the traditional space heating fire for a less polluting alternative.

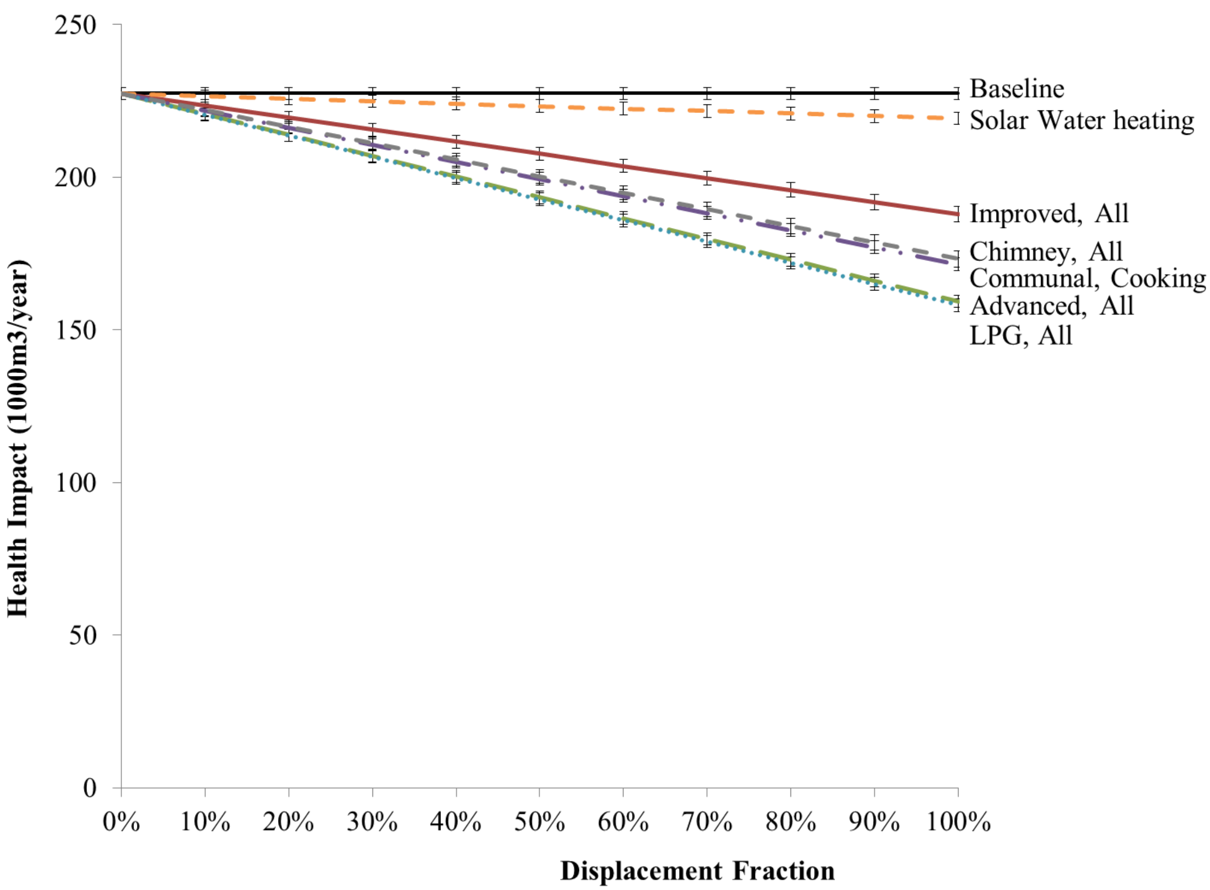

Figure 7.3 Health impacts of emissions, 95% confidence interval

The total annual climate impact is shown in Figure 7.4. Here the advanced stoves offer a smaller climate impact relative to LPG cookstoves, and the solar water heaters now offer an impact slightly more substantial than the improved stoves in this village. It is interesting to note that simply improving the efficiency of the baseline (by doubling the thermal efficiency from 16% to 32%) without designing to decrease the emission factors (pollutant emitted per MJ of fuel consumed) offers a statistically equal impact on climate as the use of highly engineered very clean-burning advanced stoves for cooking only. Therefore, designing a stove that is moderately efficient and usable for a wide array of tasks might likely create nearly the same impact on climate as designing a highly efficient, very clean burning stove.

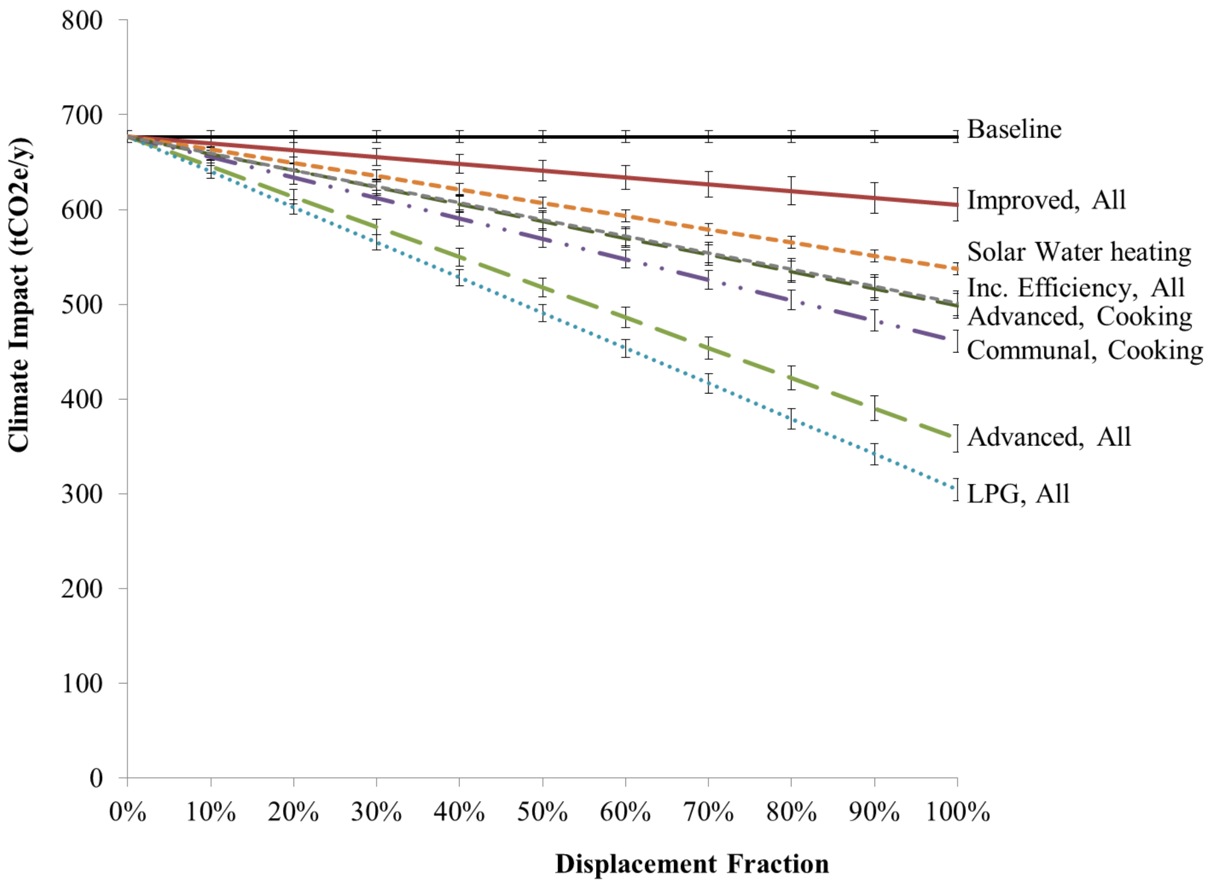

Figure 7.4 Climate impacts of emissions including Kyoto and non-Kyoto species on a 100-year timeframe, 95% confidence interval

The timeline and scope selected for the climate impact analysis also dictates the relative impacts between strategies, as shown in Figure 7.5 for the array of potential scenarios, implemented at 100% displacement for the appropriate end uses. The integrated strategy utilizing the optimal device for each end use that was developed in Chapter 5 is also presented. Inclusion of the non-Kyoto emissions (default throughout this dissertation)—including CO, non-methane hydrocarbons, black carbon, and organic carbon—increases the predicted climate impact of most of the strategies by about 50%. Much of this increase is due to black carbon with

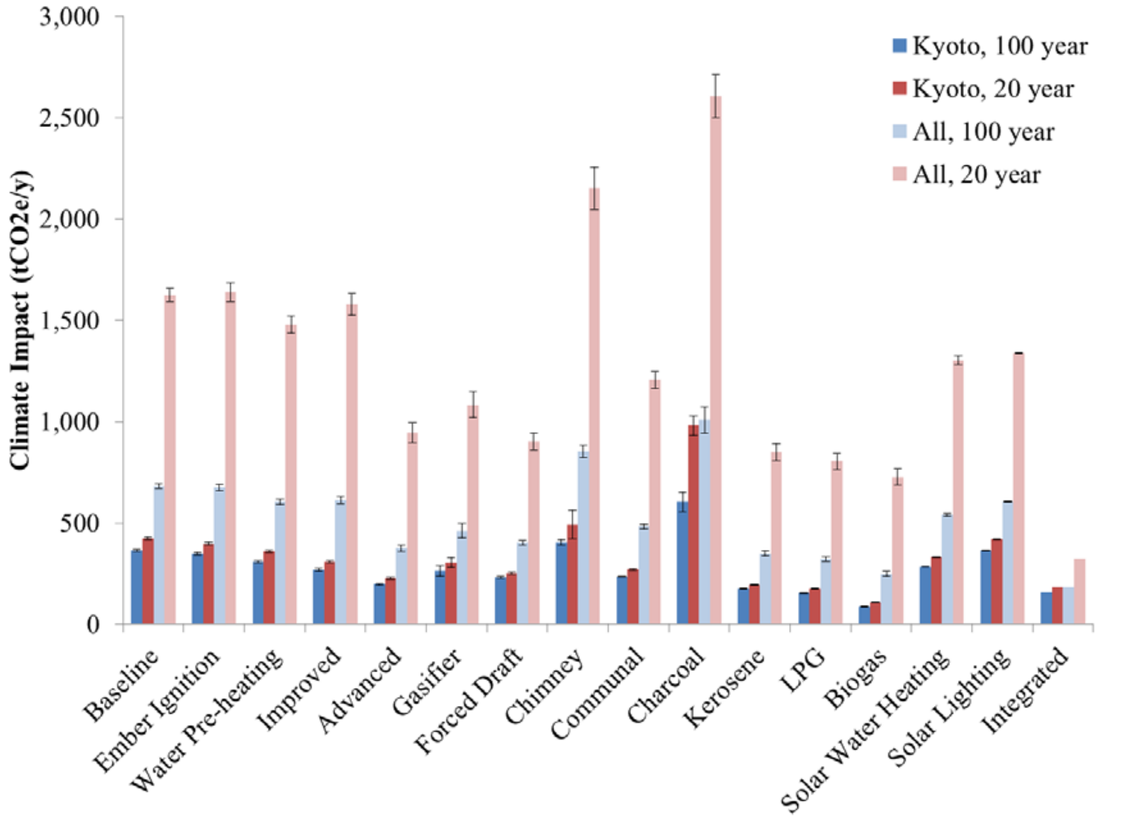

Figure 7.5 Comparison of climate impact on a 20- and 100-year time scale and including Kyoto-only and all emissions, 95% confidence interval

a GWP of 3200 and 910 at 20 and 100 years, respectively (Table 3.2). The difference between 20 and 100 year GWPs is also significant, with the 20 year impact nearly double that of the 100 year impact (the default in this dissertation) due to high levels of emissions of the fast-acting and short-lived climate species such as black carbon. As a result the stoves that reduce these species, such as the forced draft stove, have a stronger relative impact on the 20-year time frame than on the 100-year time frame. Therefore, the chosen time scale and whether or not the non-Kyoto gases can be included in the inventory may or may not change the optimal strategy. Although Smith et al. (2000) argued in favor of the 20-year scale for rural energy development programs because the use of longer time horizons would penalize near generations for the benefit of later ones, many recent studies have opted for the 100-year analysis instead (Grieshop, Marshall and Kandlikar, 2011; MacCarty et al., 2008).

Figure 7.6 shows a sensitivity analysis for the climate impact of the improved cookstove strategy in order to indicate the critical parameters. In the analysis, parameter values were varied +/- 50%, and the fuel price elasticity (β) was varied from 0 to default -0.28 to -1.00; and fuel harvest nonrenewability was varied from 0 to default 73% to 100%.

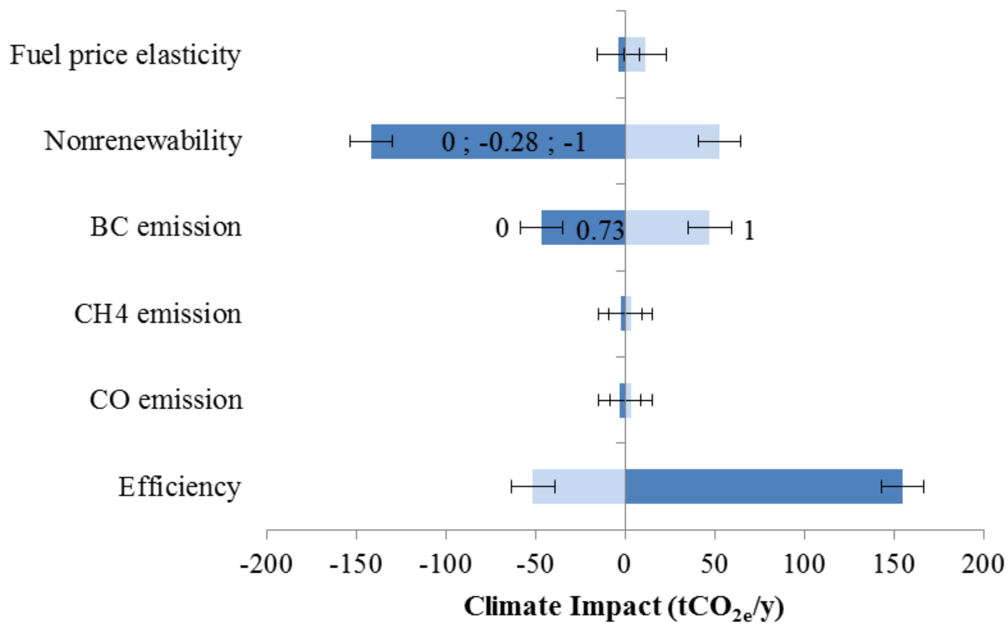

Figure 7.6 Sensitivity analysis for climate impact for improved cookstoves, 95% confidence interval

Results show that efficiency and fuel harvest renewability levels is the variable most critical to climate impacts since carbon dioxide is the most significant emission from fuel combustion. In cases of fully renewable harvest, this fraction is eliminated from the total since it is assumed to be reabsorbed by the replenished biomass stock. Because the nonrenewability fraction is most significant, implementation of tree-planting programs to reduce this fraction may have more of a total impact than reducing the emission factors from cookstoves or other fuel combustion technologies. Although black carbon emission factors are important due to their high GWP, they are still less important than efficiency and adoption. The sensitivity of gaseous emission factors has a similar magnitude to uncertainty, suggesting that highly accurate measurements of emissions may not be necessary to evaluate the choice between technological strategies at the village scale. This suggests, again, that a reasonably efficient stove that is used and paired with reforestation programs may be more effective at reducing climate impacts than a very clean burning stove that has a more narrow application.

7.5 Cost

The equivalent annual cost (EAC) of an investment in a device is associated with four components: the purchase price, the annual maintenance costs for repairs or spare parts if available, the lifetime, and the effective discount rate. Beyond this, the total effective cost also includes the operating cost of fuel and time to collect that fuel. In addition, as discussed previously, when improved lighting offers additional hours after sunset in which income-generating activities can be conducted, this financial gain is included. Figure 7.7 shows the contributions of each cost component to the total cost for the array of potential scenarios for the village as a whole, implemented at 100% displacement for the appropriate end uses. Note that space heating and lighting are included in the totals, so even the baseline scenario includes the cost of purchasing kerosene for lighting. The left side of Figure 7.7 shows the baseline and changes in practice, showing much of the expense is in time for fuelwood collection and purchase of kerosene. For the improved and other cookstoves, device purchase and maintenance cost are increased, and with the alternative fuels, the fuel purchase cost is substantial. Note that for lighting, the monthly cost of recharging the battery ($3) is taken as a maintenance cost rather than a fuel cost since solar energy itself is free. Even without the income earned through access to lighting services, the annual cost of the integrated strategy is still less expensive than the fuel cost of LPG for all uses.

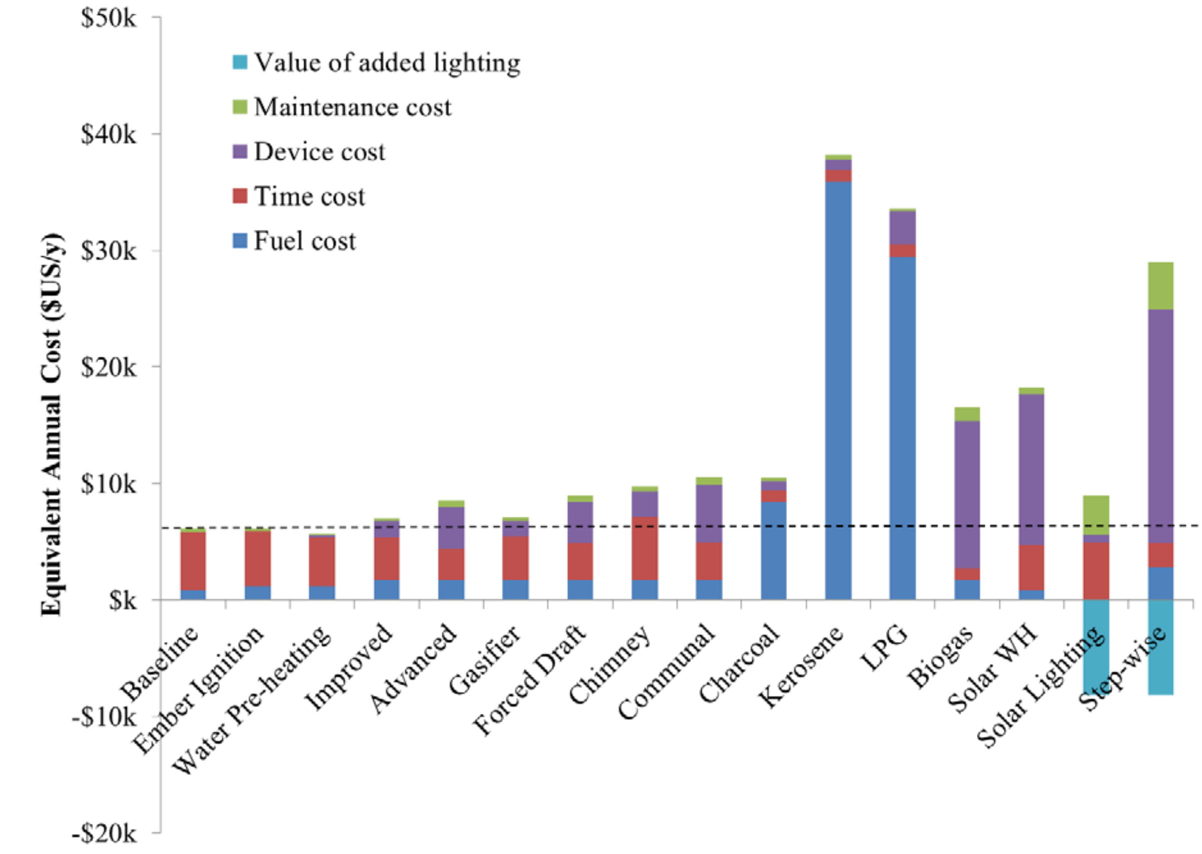

Figure 7.7 Equivalent annual cost contributions for various scenarios

It is interesting that for biomass cookstoves, the cost of the device represents about 20%-50% of the total energy service cost in the village, a magnitude roughly equal to that of the opportunity cost of fuelwood collection. This suggests a fairly equal trade-off between fuel savings in terms of time and the expense of purchasing a device. Therefore, the cost of a device should be significantly or at least recognizably less than the valuation the user places on the expected time savings. Any device that requires investments greater than returns will likely not be adopted or require other benefits that are highly valued by the user. For example, the solar lighting system offers a net income approximately equal to energy expenditures, freeing up money to meet other needs such as the installation of tin roofs on homes as was seen in the Malian village. As a result, either energy services that allow for productivity such as lighting or agricultural improvements or technologies that are inexpensive and highly efficient have the best chance of both adoption and impact.

7.6 Durability

The durability of a device dictates the useful life and its resulting equivalent annual cost. Figure 7.8 shows the impact of varying the purchase price, maintenance cost, and lifetime of a general improved stove from 50% to 150% of the baseline of $15, $1, and 5 years, respectively. It shows the EAC is most sensitive to purchase price, as expected. In addition, due to the exponential relationship, the impact due to lifetime is especially strong at shorter lifetimes. This suggests a minimum lifetime is critical to be of value to the consumer, and devices should therefore be designed to be as durable as possible.

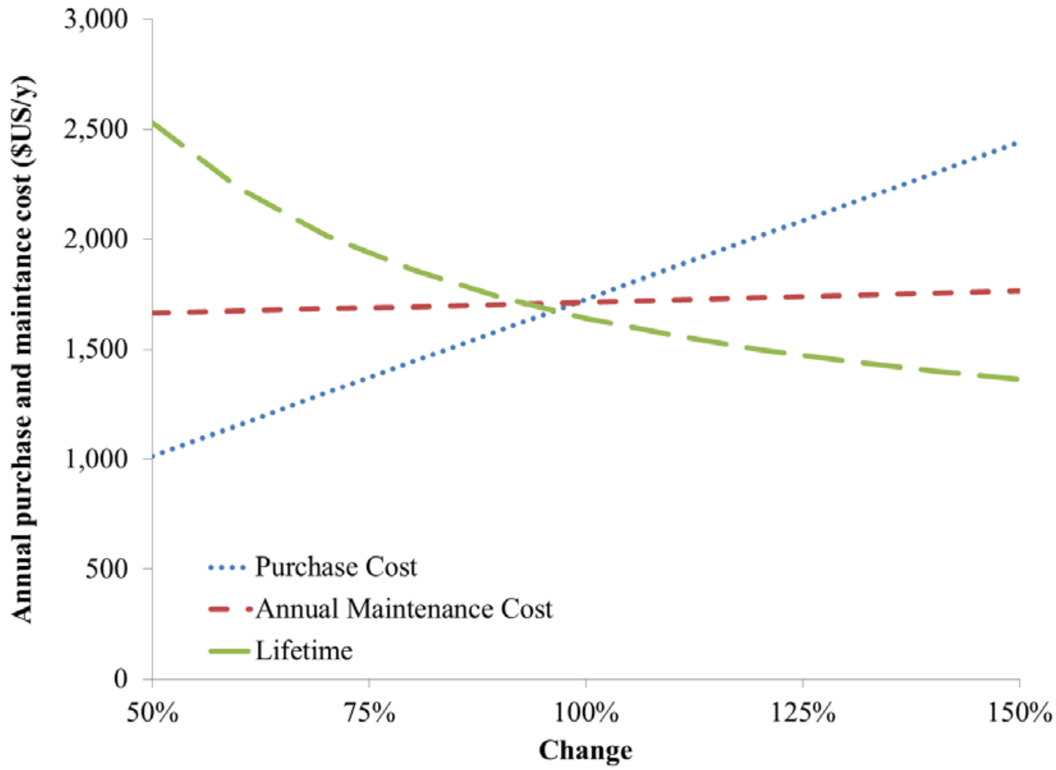

Figure 7.8 Effects of durability on total cost

In some cases, durability is increased by designing with replaceable components, such as combustion chambers, grates, or chimneys. Table 7.2 shows an analysis of the equivalent annual cost to purchase and maintain a set of improved stoves for the entire village. First is the case of a stove design with a unit cost of $40 each to purchase and a lifetime of 20 years with a $1 per year cost for maintenance each. Second is a stove design that costs only $15 and lasts for 2 years with no maintenance (no spare parts available). The equivalent cost of the more expensive and longer lasting stove with maintenance ability is 60% that of the less expensive, shorter lived option. Note this does not account for the implementation costs of setting up the program, or the potential lost community interest in improved cookstove programs that occurs when devices fail.

Table 7.2 Comparison of cookstove maintenance and lifetime

	Lifetime (y)	Purchase cost ($US)	Maint-enance ($US/y)	EAC device r=50% ($US/y)	EAC device r=5% ($US/y)	Annual cost to users ($US/y)
Improved stove without maintenance	2	$15	$0	$1,373	$840	$1,373
Improved stove with maintenance	20	$40	$1	$708	$111	$800

The analysis in this chapter investigated which of the technology design characteristics play a critical role. It was shown that usability and multi-functionality are key considerations in design. The usability analysis suggested that a technology either be specially suited to a specific task or well suited to a broad range of tasks in order to provide the largest impacts. A similar consideration is the multi-functionality of a device, which showed that the auxiliary benefits offered by the three-stone fire are valuable—estimated at half of the purchase cost of an improved stove—and must be replaced if not offered in a new technology. Otherwise, there is a good chance that the use of more polluting traditional devices may continue in addition to the new cookstove, reducing climate savings offered by an improved stove by up to 47%, health up to 13%, and cost savings by 60%. Designing with multifunction in mind may alleviate these lowered outcomes although the risk of the device being used for its secondary purposes alone may represent a less efficient way of providing those services.

In terms of more technical design considerations, it was shown that incremental improvements in the thermal efficiency of existing devices is less likely to impact fuel use than adoption and use of devices that do not use fuelwood at all. In terms of emissions, health is impacted more by targeting the tasks that create the most HAP (in this case space heating) than by incremental improvements in emission factors when the effects of usability and adoption are considered. Similarly, the impacts on climate are more related to reductions in fuel use than emission factors; therefore, designing a stove that is efficient and usable for a wide array of tasks might likely create nearly the same impact on climate as designing a highly efficient, very clean burning stove. In addition, because the fuel harvest non-renewability fraction is the most significant factor to climate impact, implementation of tree-planting programs to reduce this fraction may have more of a total impact than reducing the emission factors from cookstoves or other fuel combustion technologies while also providing potential employment in the community.

Finally, the economic considerations of cost and durability showed, first, any device that requires investments greater than returns will likely not be adopted or require other benefits that are highly valued by the user. For example, the solar lighting system offers a net income approximately equal to the energy expenditures, freeing up money to meet other needs such as the installation of tin roofs on homes as was seen in the Malian village. As a result, either energy services that allow for productivity, such as lighting or agricultural improvements, or technologies that are inexpensive and highly efficient have the best chance of both adoption and impact. And second, the lifetime of a device is an important factor. A more expensive technology that has a long lifetime and can be maintained at a modest cost represents a lower cost to the user than a less expensive one with a limited lifetime in addition to serving as a more sustainable and long-term solution.

CHAPTER 8

THE IMPACT OF FACTORS INFLUENCING ADOPTION OF HOUSEHOLD ENERGY TECHNOLOGIES

No matter the potential performance, a technology will not make an impact if it is not adopted and used. Therefore, understanding adoption factors is important to predicting overall outcomes. As seen in Chapter 2, factors relating to adoption include community demographics, motivation, and affordability of the technology, and rebound and stacking of fuels and devices. These directly impact the displacement fraction of a new technology and therefore have a proportional relationship to the impact in the village.

8.1 Demographics

There are a number of demographic variables in communities that are expected to affect the adoption rates of improved energy services, including income, family size, education, and others. There are dozens of studies in the literature that relate household income to fuel mix and energy consumption across the globe by using econometric models, including Ramachandra et al. (2000), Sehjpal et al. (2014), and Gupta and Kohlin (2006). These and other studies often find a negative correlation between household size and energy use per capita, and that as education and household income increase, use of fuels of increased cost and convenience (such as biogas, LPG, and finally electricity) also increase.

In the Malian village used in this analysis, families are polygamous and often share cooking duties. As a result, the family size is an average of 770 residents divided by 123 women who are responsible for cooking, or an average of about 6.25 people per cook. Not every woman cooks every day, and each woman generally has her own cooking equipment. Many women share a kitchen, for a total of 97 devices required to reach all residents in the community, or about 8 people per cookstove (Johnson, 2012). In other communities, the household size may be smaller or larger, and the number of cooking devices required and their capacity would be different. Figure 8.1 shows that the cost to purchase and maintain devices decreases with increasing family size for all non-community-based devices (such as water heaters) since less devices per person are needed in the community. It should also be considered that energy use per capita also decreases with increasing family size for the same reasons. This leads to the conclusion that more expensive devices and fuels should perhaps be promoted in regions with larger family sizes due to the lower cost of implementation in the community and the largest economies of scale in terms of both device and fuel purchase costs.

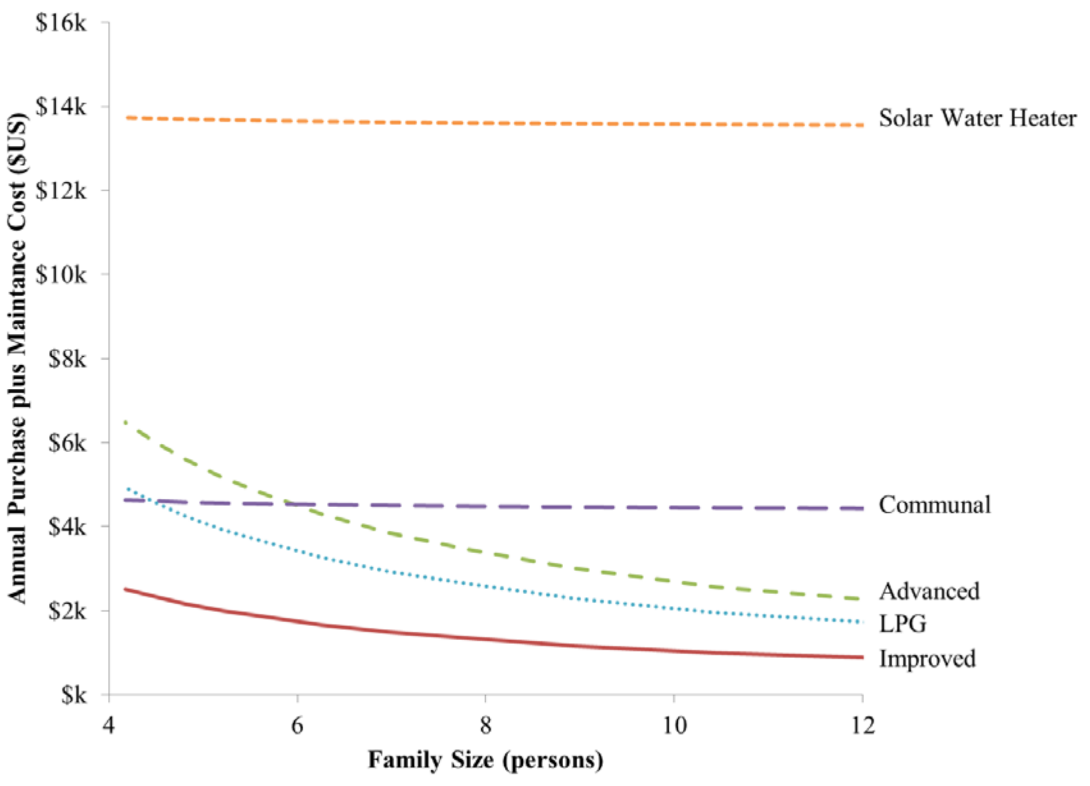

Figure 8.1 Annual device purchase and maintenance cost as a function of family size

8.2 Motivation to Adopt

An overall metric for willingness to adopt is the quality of life offered, a metric created from qualitative rankings of desirability, disruption, convenience, and safety. This metric is important because it can be seen as a proxy for the likelihood of adoption. A score of 5 represents the baseline situation, a higher score represents an improvement and a lower score than 5 represents a reduction. These ratings are reported as the average and are weighted by baseline energy use for all investigated uses in the village, with the overall quality of life represented by an equally weighted average of the four components as estimated by the author. Notice the solar water heaters and LPG cookstoves offer the largest potential overall improvements because they are so desirable to use and can account for large fractions of energy use. Most of the biomass cookstove designs, however, offer little change from a score of 5 because they represent a reduction in score by causing a user to need to change their cooking habits paired with reduced convenience while at the same time increasing desirability and safety. The quality of life offered by solar community lighting is low due to the relatively low energy use in the weighting metrics although clearly a significant improvement in quality of life and resulting adoption rate is expected.

One method for increasing a consumer's motivation to adopt is the implementation of use-based incentives. For example, an NGO in India called Seva Mandir found that offering two pounds of dal at each visit to the community nurse increased vaccination rates sevenfold (Banerjee and Duflo, 2011). In the energy service sector such incentives could include offers of food or cooking utensils in exchange for continued use of cookstoves. The application of incentives for energy efficiency, demand-response, and renewable energy projects in the form of rebates or tax incentives is common for energy services in developed nations. Further research into the application and efficacy of incentives in the rural energy development context is needed.

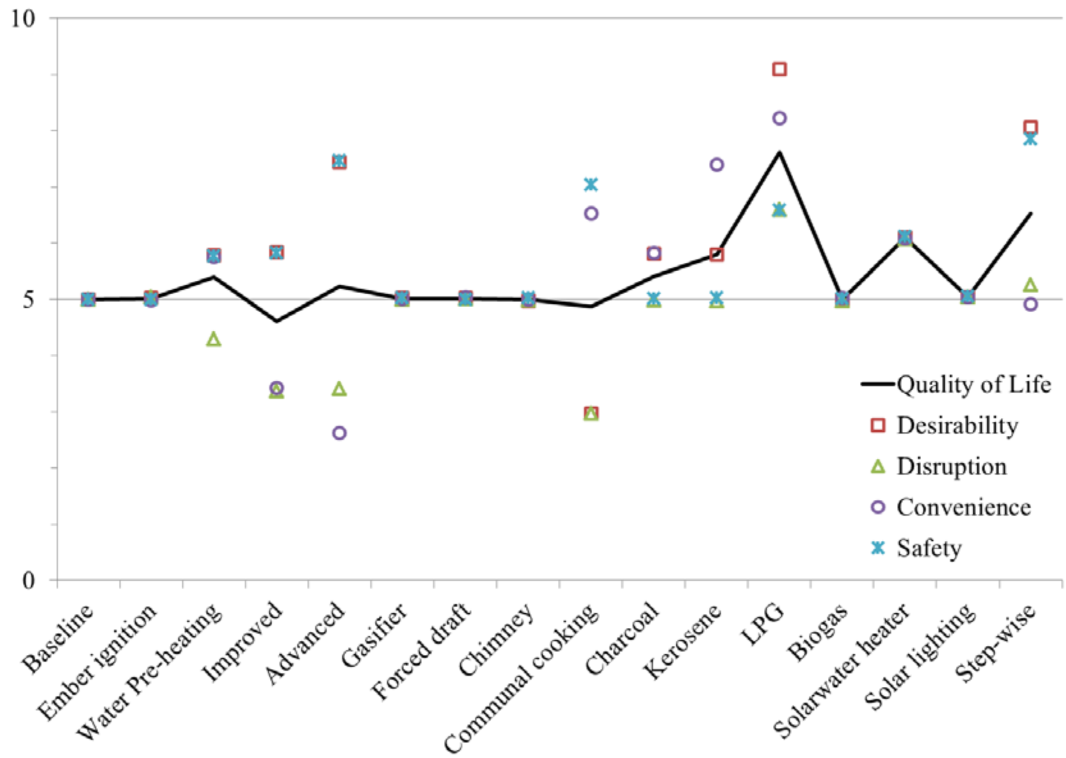

Figure 8.2 Overall quality of life and components of various scenarios relative to the baseline of 5

8.3 Affordability

A major criterion for adoption is that the device is affordable and worth the investment, which is indicated by a number of metrics. These include the perceived cost in terms of true user discount rates (Table 8.1) and the payback period (Table 8.2). Table 8.1 shows the perceived equivalent annual cost to purchase, maintain, and provide non-collected fuel for several types of devices incorporating both their lifetime and the perceived discount rate for the household. This does not include the value of the opportunity cost of time. It is interesting that even for the inexpensive improved cookstoves, the high discount rate in a liquidity-constrained household makes the purchase price 20% more expensive than it does to consumers with more cash reserves available. The solar water heater is most sensitive to the discount rate as it has a high purchase price, long lifetime, and no fuel costs. LPG cookstoves, on the other hand, have a relatively modest upfront cost and high ongoing fuel purchase costs, making the effective price nearly insensitive to the discount rate. However, these fuel purchases must be in full cylinders, requiring cash savings to purchase fuel in bulk rather than incrementally as needed, as is possible with kerosene.

Table 8.1 EAC ($US/y) as a function of discount rate

	Improved	Advanced	Communal	Solar water heater	LPG	Lighting	Step-wise
r=5%	$2,812	$4,423	$3,670	$4,042	$30,411	$3,422	$12,513
r=50%	$3,333	$5,780	$7,291	$14,398	$32,523	$4,001	$26,916
Factor	1.2	1.3	2.0	3.6	1.1	1.2	2.2

Table 8.2 shows the payback period and income fraction for various strategies. Payback period is determined from the value of time and fuel cost savings relative to the cost of the equipment. Income fraction is determined from the monthly fuel and device purchase/maintenance costs for each family with an annual income assumed from one household member employed at the going labor rate for 40 hours per week 4 weeks per month. It does not account for the value of time savings. One indicator of energy poverty is spending 10% or more of income on energy (Barnes, Khandker, and Samad, 2011). As seen, the payback and income fraction for the improved, advanced, and communal scenarios are between 3 and 9 years, suggesting their lifetime must be at least this long in order to recoup the cost of purchase. Purchase expense is between and 14 and 30% of income, still placing the households in energy

poverty. However, the solar water heater will take nearly 24 years to payback in terms of fuel savings alone at a cost of 60% of income. The cost of LPG is 33% greater than the default monthly income; therefore, payback is never achieved, and adoption is impossible without significant subsidies. The cost of the lighting system is recouped after about 7 years if the value of income generation is not included, and only about 8 months if the income that is produced is considered. And because this income generation is made possible, income increases and the income fraction for energy services is reduced to 9%, or lower than one suggested measure of the energy poverty line. Due to the high cost of purchasing multiple devices, the payback period of the integrated strategy is nearly 40 years, but the income fraction is less than the solar water heater alone due to the additional income.

Table 8.2 Payback period (y) and income fraction

	Improved	Advanced	Communal	Solar water heater	LPG	Lighting without added income	Lighting with added income	Step-wise
Payback Period	4.3	3.5	8.9	23.8	-0.1	7.4	0.7	42.4
Income Fraction	14%	24%	30%	59%	133%	17%	9%	56%

Figure 8.3 shows a sensitivity analysis for the equivalent annual cost of the improved cookstoves. Each input parameter was varied from 50% to 150% of its default value for the cost analysis with the exception of the user discount rate, which was 5%, 50%, and 100%. It shows that the value of time in terms of labor rate and shadow value are the most critical factors to equivalent annual cost. Displacement and the number of cooks are also more critical than the purchase cost and discount rate. This suggests, as expected, that the affordability of a technology

in a community is primarily dependent on the availability of paid work opportunities followed by the time required for fuelwood collection.

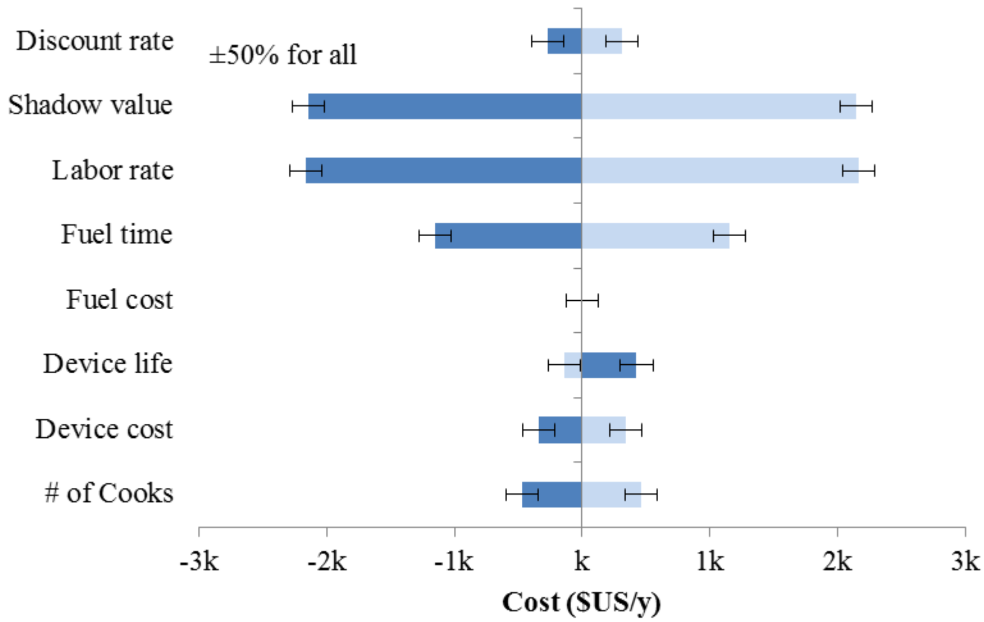

Figure 8.3 Sensitivity analysis for equivalent annual cost interval for improved cookstoves, 95% confidence interval

The potential health and greenhouse gas savings and associated costs at the default user discount rate of 50% both including and excluding the opportunity cost of time are shown in Table 8.3 at full displacement. Costs excluding the opportunity cost of time represent the capital costs only, and inclusion of opportunity costs accounts for the time savings afforded to the user. A negative value indicates a net expense and a positive value indicates a net monetary savings due to reduced opportunity cost relative to the present situation. Incremental costs are the total cost divided by the potential savings, indicating the cost per ton of CO_{2e} abated or RHI reduction. Results show that LPG cookstoves offer the greatest potential climate savings at the greatest cost per ton, whereas advanced cookstoves offer nearly 90% of the savings at the lowest cost per ton, another reason advanced cookstoves are currently the subject of great attention. The advanced cookstoves represent the most cost effective option in terms of climate, but the improved stoves are slightly more cost effective for the relative reduction of health hazards. LPG and solar water heaters are extremely expensive, and solar lighting is the only strategy to potentially offer a net income while reducing impacts to health and climate. The integrated strategy has a relatively high cost for abatement due to the purchase of multiple devices, but interestingly, the incremental costs are not as high as using LPG cookstoves or solar water heaters alone since such a significant impact to climate and health is expected.

Table 8.3 Annual cost with and without opportunity cost of time ($US/y), potential carbon abatement (tCO_{2e}/y) and incremental cost ($US/$tCO_{2e}$), potential health abatement (m^3/y) and incremental cost ($US/$m^3$), with 95% confidence for 1000 iterations

	Cost		**Climate**			**Health**		
	Total cost w/o opportunity cost	Total cost with opportunity cost	Potential Abatement	w/o opp.	with opp.	Potential Abatement	w/o opp.	with opp.
	$US/y	$US/y	tCO_{2e}/y	$US/$tCO_{2e}$		1000m^3/y	$US/$m^3$	
Improved	-$2,190 ± -$111	-$930 ± -$43	71 ± 18	-$31	-$13	47 ± 0.02	-$0.05	-$0.02
Advanced	-$4,637 ± -$275	-$2,409 ± -$167	308 ± 15	-$15	-$8	71 ± 0.01	-$0.07	-$0.03
Communal	-$6,148 ± -$119	-$4,456 ± -$23	200 ± 12	-$31	-$22	56 ± 0.01	-$0.11	-$0.08
LPG	-$31,380 ± -$513	-$27,471 ± -$397	360 ± 12	-$87	-$76	71 ± 0.01	-$0.44	-$0.38
SWH	-$13,254 ± -$342	-$12,163 ± -$234	143 ± 6	-$93	-$85	8 ± 0.01	-$1.59	-$1.46
Lighting	-$2,858 ± -$252	$5,334 ± -$311	77 ± 2	-$37	$69	9 ± 0.00	-$0.31	$0.58
Integrated	-$25,773 ± -$822	-$14,712 ± -$440	500 ± 6	-$52	-$29	89 ± 0.01	-$0.29	-$0.16

Because the figures reported in Table 8.3 are strongly coupled to the underlying assumptions, Figure 8.4 shows the cost relationship to the most critical assumption, the potential labor rate. Note that a shadow value of 50% is applied to this rate. The labor rate of zero indicates the results of the analysis if the opportunity cost of time is not considered. In areas or households where time has a low value due to the lack of employment opportunities or skills, the baseline scenario is the least costly, as expected. At the income level of skilled labor such as a blacksmith or similar artisan at $4/day, the least costly option for the user transitions from the baseline to improved or advanced cookstoves. It is only at this point where the time savings offered by increased fuel efficiency justify the purchase cost of a new

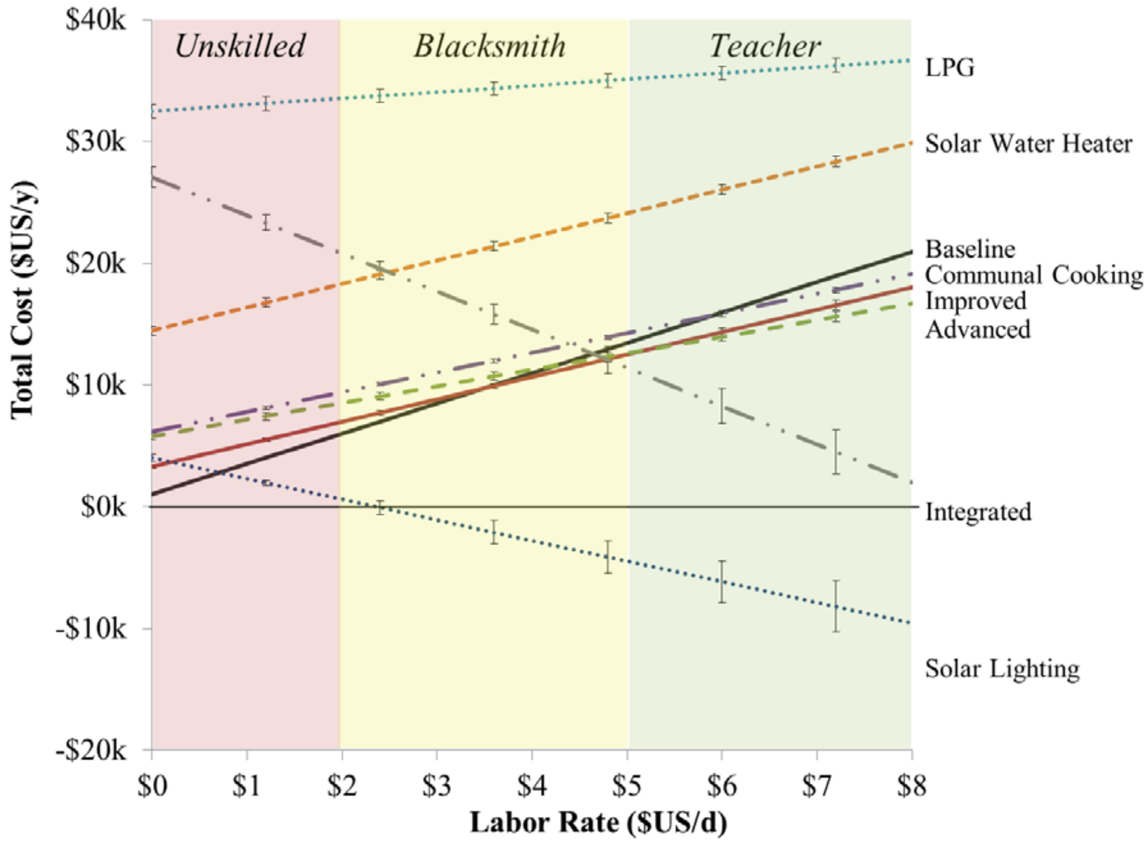

Figure 8.4 Total annual cost ($US/y) as a function of community labor rate ($US/d) for various scenarios

device, providing an explanation as to why the limited uptake of market-based improved cookstoves has been seen in the past—consumers understand that the added expense is not justified by fuel savings alone. The additional fuel savings offered by the advanced stove over the improved stove make its annual cost less expensive beyond this labor rate as well. As labor rate increases, additional options become less expensive than the baseline, justifying their purchase through more rapid payback.

It is interesting that, in addition to offering monetary savings in relation to the baseline, the installation and use of the solar lighting system becomes a net income rather than an expense at the unskilled labor rate of about $2.50, which is approximately the wages earned for weaving baskets to sell at the market. This continues to assume a shadow value of 50%, indicating that work is only available for half of the time it is possible to work. This analysis supports the observation from the field that income was generated in the village as a result of the addition of the solar lighting system. At some point, factors other than time savings become more important since the time savings alone of the solar water heater or LPG cookstove do not justify the cost to purchase and operate, and therefore, other factors leading to adoption must dominate.

One method of financing energy services in developing countries is via carbon credits through the Clean Development Mechanism. Because the market value per ton of CO_{2e} fluctuates, Figure 8.5 shows the comparison of the total equivalent annual cost if the payments received for carbon offsets are included versus the going rate for those credits assuming full displacement of technologies and a labor rate of $2 per day.

The integrated strategy represents the lowest cost of all the options beginning at the labor rate of a moderately skilled worker, which is not too high but beyond that of most members in this community. However, the presence of outside subsidies applied to the purchase cost of devices could shift this line down, making it less expensive than the improved cookstove or baseline at lower levels of income. The application of subsidies has the potential to dramatically transform the energy landscape, as it continues to do in the US for both oil and renewable energy sources, for example.

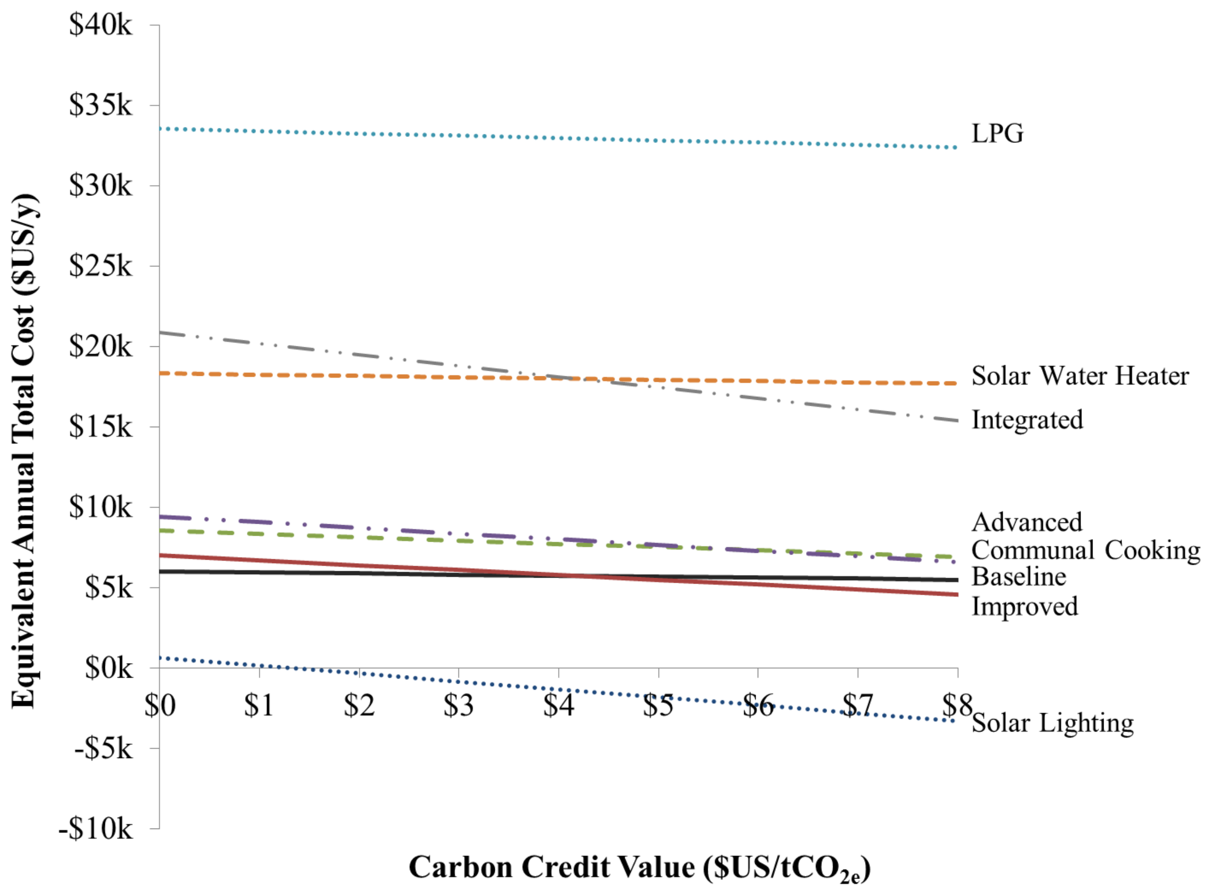

Figure 8.5 Total annual cost including carbon offsets ($US/y) as a function of carbon credit value (US/tCO_{2e}$) for various scenarios

Because LPG is such a desirable strategy given other metrics such as energy, climate, and health savings, its market price is often subsidized to make it more accessible to users. Table 8.4 represents a phase diagram showing the least costly strategy option to the user as a function of the daily labor rate and subsidy level for LPG. It shows that no matter the subsidy, the cost of purchasing an improved, advanced, or LPG stove is simply not paid back for the lowest income sectors. There is a brief range where the improved stove is optimal, which is followed by a large range at higher incomes where the advanced stove pays for itself in terms of time savings. LPG is not affordable to even the highest income group unless subsidized at a rate higher than 80% of the assumed price. Subsidies for the price of cookstoves or other devices can be analyzed in a similar fashion.

Table 8.4 Phase diagram for minimal total annual cost

LPG Subsidy	Labor Rate ($US/d) $ -	$0.80	$1.60	$2.40	$3.20	$4.00	$4.80	$5.60	$6.40	$7.20	$8.00
0%	Base	Base	Base	Base	Base	Impr	Impr	Adv	Adv	Adv	Adv
10%	Base	Base	Base	Base	Base	Impr	Impr	Adv	Adv	Adv	Adv
20%	Base	Base	Base	Base	Base	Impr	Impr	Adv	Adv	Adv	Adv
30%	Base	Base	Base	Base	Base	Impr	Impr	Adv	Adv	Adv	Adv
40%	Base	Base	Base	Base	Base	Impr	Impr	Adv	Adv	Adv	Adv
50%	Base	Base	Base	Base	Base	Impr	Impr	Adv	Adv	Adv	Adv
60%	Base	Base	Base	Base	Base	Impr	Impr	Adv	Adv	Adv	Adv
70%	Base	Base	Base	Base	Base	Impr	Impr	Adv	Adv	Adv	Adv
80%	Base	Base	Base	Base	Base	Impr	Impr	LPG	LPG	LPG	LPG
90%	Base	Base	Base	Base	Base	LPG	LPG	LPG	LPG	LPG	LPG
100%	Base	Base	Base	LPG	LPG	LPG	LPG	LPG	LPG	LPG	LPG

8.4 Rebound

The effect of rebound can range from very little to nearly doubling consumption in the cases of suppressed demand for lighting. In the case of cookstoves in a typical village with a default fuel price elasticity (β) of -0.28 from the literature, Table 8.5 shows rebound increasing energy demand by 2% for an improved stove and 7% for an advanced stove. However, there are some communities with a significantly higher fuel price elasticity, such as the maximum value of β of -1.77 observed in Uganda by Egeru et al. (2010). If this level of elasticity was present in the Malian village, rebound would account for 16% and 45% of the energy use in the improved and advanced cookstove scenarios, respectively. High rebound is often due to suppressed demand, where a lack of affordable energy leads to users foregoing meeting their energy needs. Thus when energy prices drop (or efficiency increases) this forgone energy is now accessible. These increases in consumption represent a proportional decrease in savings for climate, health, and opportunity cost as well. However, because they still provide an increase in available energy services, one objective of the program is met, and the consumer is pleased and therefore is more likely to adopt the device that gives her more resources. In communities where high rebound is expected, the relative benefits of strategies will differ than those expected via direct fuel savings alone.

Table 8.5 Energy for cooking (GJ/y) as a function of fuel price elasticity

Cooking Energy (GJ/y)		β=0	β=-0.28		β=-1.77	
		Value	Value	% Increase	Value	% Increase
Baseline	Consumed	2,203				
	Delivered	355				
Improved	Consumed	1,425	1,460	2%	1,654	16%
	Delivered	355	366	3%	426	20%
Advanced	Consumed	852	912	7%	1,236	45%
	Delivered	355	383	8%	535	51%

8.5 Stacking

Consumers intuitively know how to maximize the use of their time and resources. This is often done by stacking fuels and devices, using the most efficient and convenient device for each task as needed and affordable. For example, in modern kitchens, there are a number of specialized devices from rice cookers to bread machines, coffee makers and toasters. In developing households, this is akin to those who can afford to purchase a cylinder of LPG to first use it for small fast tasks such as steeping tea and then progress to using them for more intensive uses as income allows. Given this theory and observation of fuel and device stacking, it is likely that several specialized devices will ultimately be more effective than one device that attempts to meet all needs, as was seen in the analysis of the integrated strategy. With this in mind, stacking becomes not a challenge to be overcome but an opportunity to make a larger impact than a single strategy could. For example, as was seen in Table 8.3, despite the cost of purchasing multiple devices, the incremental cost of climate and health abatement is reduced through an integrated strategy from what it would be with solar water heaters or LPG cookstoves alone. And as was seen in Figure 6.3, the relative cost of an integrated strategy rapidly decreases with increasing income and opportunity cost of time. This is because allowing opportunities for income generation through improved energy services in turn enables the user to better afford the optimal devices to meet their basic energy needs through stacking of devices best suited to meet their needs.

Because a device that is not used will not make an impact, this chapter investigated the system-level factors that influence the rate of adoption. It was shown that consumers are more likely to adopt technologies such as solar water heaters, which are convenient, safe, and modern, whereas those that require additional time or effort are less likely to be accepted. A motivated consumer must also be able to afford the technology. Affordability of a technology in a community is primarily dependent on the availability of paid work opportunities followed by the time required for fuelwood collection. The payback of most cookstoves is greater than three years, suggesting the lifetime must be at least that in order to make the investment worthwhile. However, income fraction is still greater than one marker of energy poverty considered by Barnes Khandker, and Samad (2011) which defines energy poverty as spending 10% or more of income on procuring energy services. The income fraction and payback period of solar water heaters and LPG cookstoves put those technologies out of reach from the economic perspective of the user. Solar lighting, however, has a relatively short payback period, and when the income generation made possible by adequate lighting is included, the payback takes only 8 months, and the family is lifted above the energy poverty line.

Access to improved energy services often results in rebound, which reduces anticipated energy savings and impacts but also results in increased access to energy services. The stacking of multiple devices in the household is commonplace and is beneficial because devices most suited to the task at hand are used in favor of those less suited due to usability and preference issues. Allowing opportunities for income generation through improved energy services in turn enables the user to better afford the optimal devices to meet their basic energy needs. When expensive LPG and solar water heaters are paired with biomass cookstoves and solar lighting systems, impacts are increased and costs are reduced. In addition, the adoption rate will be high due to the natural progression of meeting the aspirations and needs of the community.

CHAPTER 9

CONCLUSIONS AND FUTURE WORK

Mugendi M'Rithaa of Cape Peninsula University of Technology shared a proverb from Sierra Leone at the American Society of Mechanical Engineers 2015 Engineering for Global Development Keynote that states "A razor may be sharper than an axe but it cannot cut wood." This adage captures the importance of consideration of the task at hand when choosing a strategy rather than focusing on the precision of the technology alone. As seen in the previous chapters, there are a variety of technological strategies ranging from simple changes in practice to advanced engineered devices that have the potential to reduce the costs and associated impacts to health and climate of energy usage. However, the outcomes produced by these technologies are dependent on more than technical performance alone and must be analyzed in the context of the greater village energy system including factors relating to design, application, and adoption.

Because there are limited resources to support the research, development, and implementation efforts needed to provide clean and sustainable energy services for the nearly 40% of the world's families living in energy poverty, these resources must be allocated effectively in the pursuit of strategies that can make a significant difference. Such strategies will involve devices that both perform well and are sought out by the user. These solutions can be identified through the use of a holistic approach involving systems level modeling paired with identification of the energy service needs and the drivers of adoption and sustained use in a community. Therefore, the research questions may not only be about designing an optimally-performing device in the laboratory, but also about understanding and adapting to the factors that dictate its use, performance, and ultimate impact in a community.

Although there is an immense need and growing international funding for the reduction of energy poverty through improved energy services, the tools necessary to approach design in such a manner have not been previously available. To address this need, the systems model developed here provides a comprehensive analysis of potential strategies with particular emphasis on effectiveness as well as the social dimensions that reflect user acceptance. Development of this model began with an overview of an energy system in a typical rural developing community. It investigated the large parameter space including a variety of energy needs, potential technologies to meet these needs, and local variables relative to outcomes in terms of comprehensive technical, environmental, economic, and social objectives. Unlike many models developed previously, this model accounted for the system-level design, application, and adoption factors in the community such as usability, stacking, rebound, multi-functionality, opportunity cost, discount rate, and the improvement in quality of life offered to the user. In addition, each end use of energy and its impacts were modeled separately and compiled at the annual village scale to report the overall outcomes created by of a variety of common technological energy service strategies.

9.1 Conclusions

The analysis was conducted primarily in the context of a well-characterized village in Mali with a population of 770. In this village, household energy consumption is approximately 4.4 TJ/y. Of this, 51%, 7.5%, 22%, 19%, and less than 1% are used for cooking, specialty cooking, water heating, space heating, and lighting, respectively. In the baseline scenario, this energy use is responsible for a forest harvest rate of 315 metric tons per year, emissions of 680 metric tons of CO_{2e}, and a cost of fuel and time opportunity equivalent to $5,800 in the village each year. Relative to the local bank holdings of less than $2,000, this is a considerable expense (Johnson and Bryden, 2012a). Although lighting represents a small share of energy consumption, the cost of kerosene is substantial and represents nearly all of the monetary energy expenses in the household, and the black carbon emissions from wick-based kerosene lighting create a significant climate impact as well. Even in this village near the equator, the unventilated fires for heating during the cool season are responsible for the largest detriment to health in this analysis.

The outcomes of common technological strategies including biomass cookstoves, LPG cookstoves, solar water heaters, and solar-charged lighting systems were investigated in Chapter 5, which showed that no single strategy could optimally address all objectives. This analysis revealed that improved biomass cookstoves can provide modest improvements in energy, climate, and health, yet the fuel savings do not quickly justify the purchase cost, and the quality of life to the user is slightly reduced, limiting the motivation to adopt. Advanced cookstoves can offer two times greater fuel savings and four times greater climate and health emission reductions relative to improved stoves if used for all energy tasks, yet the limited usability for water heating and other specialized tasks is likely to reduce this substantially. The use of communal cookstoves is the optimal method of cooking in communities where it would be acceptable. Solar water heaters eliminate the energy use and emissions for heating water, a significant fraction in the household; however, the devices are expensive and impacts to health are small since heating water is generally done outdoors. Use of LPG cookstoves has the most beneficial impacts in terms of energy use, climate, health, and social aspects, yet the high upfront and ongoing fuel costs prevent its use for more than a few small tasks. The community-charged solar lighting system, on the other hand, costs about the same as biomass cookstoves to purchase, but due to the potential for income generation resulting from its installation, approaches a net zero cost to the users.

An integrated strategy developed based on a feasibility analysis from the user's perspective had the greatest potential for impact and likely user acceptance because it follows the natural progression typically seen in communities as availability and income allow. In this strategy, cooking is conducted using the most acceptable biomass-fueled cookstove, whether it is improved, advanced, or communal. Specialty cooking tasks such as steeping tea were assigned to LPG since observations in many countries have shown that when LPG is available and affordable, it is often used for small tasks as opposed to daily cooking of meals. Solar water heaters are a long-term solution that essentially eliminates the fuel combustion and emissions for 20% of the energy consumed in the village. Finally, off-grid lighting for productive and income-generating opportunities after sunset is one of the services requested most by the community members in this village and as a result can offer great improvements to well-being and quality of life. A combination of these devices developed into an integrated strategy would be user-driven, provide significant improvements in outcomes, and most likely enjoy widespread adoption. It is more costly, however. From the user's perspective, at a 50% discount rate the purchase and maintenance of these devices would require an annualized investment of $24,000 for the village, whereas at the social planner's discount rate of 5% this would be reduced to about $10,000 per year. This equates to about $12-$13 per person per year of external funding to provide the entire village with all of the physical devices needed to optimally meet their energy needs at the same current cost to the users in terms of time and money. This does not include overhead costs of implementation, which if included even at as much as two times the material (device) cost would only result in a total per capita cost of $25-$35 per year. In comparison to the $110 per person per year estimated as the external funding needed to implement comprehensive interventions in the millennium villages (Millennium Project, 2015), $30 for clean and sustainable energy services is a relatively low figure.

Chapter 6 illustrated the importance of considering application during the selection process for energy technology strategies. It showed that understanding the specific needs in a community is essential to choosing an appropriate strategy, as are awareness of the condition and availability of the local fuel supply. It also considered that precision testing in a laboratory setting is unlikely to translate to statistically separable differences when placed within the village energy system. To better understand the sources and contributing factors of uncertainty from the technology performance and local energy needs and variables, an uncertainty analysis can identify where precision is needed and where it is not in order to identify parameters that change the outcome or decisions.

The analysis in Chapter 7 investigated the impact of technology design characteristics on outcomes. It was shown that usability and multi-functionality are some of the most significant factors, suggesting that a technology either be specially suited to a specific task or well suited to a broad range of tasks in order to provide the largest impact. The auxiliary benefits offered by the three-stone fire are highly valued and if not provided for, the use of more polluting traditional devices may continue in parallel, which would reduce impacts substantially. It was also shown that incremental improvements in the thermal efficiency of existing devices is less likely to impact fuel use than the adoption and use of devices that do not use fuelwood at all. Similarly, incremental improvements in emission factors have less of an impact on health than targeting the tasks that create the most HAP and have the greatest impact on climate, which is most impacted by reductions in fuel use and nonrenewability factors. Technologies designed at cost levels that offer outcomes more highly valued than investment costs are needed, whether these benefits come in the form of fuelwood savings, lighting for productivity, or other social benefits. Finally, durability and longevity of solutions are essential to increase affordability and sustain impact.

Because a device that is not used will not make an impact, Chapter 8 investigated the system-level factors that influence the rate of adoption. Technologies that are convenient, safe, modern, and affordable increase likelihood of adoption, whereas those that require additional effort or a change in practice are less likely to be accepted. The payback period of most cookstoves is greater than three years, suggesting its lifetime must be at least that in order to make the investment justifiable to the user. The income fraction and long payback period of solar water heaters and LPG cookstoves put those technologies out of reach from the economic perspective of the user, yet they remain an aspirational product for other reasons such as convenience. Community-charged solar lighting systems, however, have a relatively short payback period, and the income generated helps to reduce energy expenditures to below 10% of income, one definition of the threshold of energy poverty. Although the effect of rebound reduces anticipated savings, it provides a benefit and fulfills one goal of increased access to energy services.

Finally, although often considered a barrier to dissemination of improved cookstoves, the stacking of multiple devices in the household is commonplace, and it is beneficial because devices most suited to the task at hand are used in favor of those less suited due to usability, preference, and performance issues. Allowing opportunities for income generation through improved energy services such as lighting in turn enables the user to better afford optimal devices to meet their basic needs for thermal energy. When expensive LPG cookstoves and solar water heaters are paired with biomass cookstove and solar lighting systems, impacts are increased and operating costs are reduced. In addition, the adoption rate will be high due to the natural progression of meeting the aspirations and needs of the community. The outside investments required to provide all of the necessary devices are relatively small at $13/person/year, yet the array of benefits from the local to the global scale are significant.

9.2 Future Work

Having addressed the need for a basic comprehensive framework and modeling capability at the community scale, there are a number of areas where future work can progress to increase fidelity, accuracy, and application of the model. Suggestions for future work primarily involve increasing the level of detail and flexibility in the model, development and use of field surveys and databases, validation of the model through field studies, and broadening the application to additional analysis types and energy systems settings.

The present model uses fairly simple equations to quantify outcomes while future work can include increasing the level of detail based on pre-existing or newly-developed models. These may include, for example, the WHO model to predict health impacts, socioeconomic models of product diffusion and adoption, econometric models of rebound specific to the energy sector, detailed models of technology performance, fuel harvest renewability models, and others. Engineering design techniques, such as models for user needs and preference on the input side, optimization techniques on the output side, and exploration of the design space can be applied as well. A high-fidelity collection of models such as this will help to analyze the impacts of changes to one component or input variable on the outcome within the entire system.

Inputs to the model were based on estimates and generalized information available in the literature. In the future, use of the model should include gathering additional village-specific data empirically through measurements and surveys. One of the most important parameters is the displacement fraction, which must be understood and predicted from the perspective of the user. Ethnographic surveys can be developed to capture the social aspects of the most significant needs, anticipated adoption rates, and benefits valued in a community. This may lead to the development of correlated parameters for expected displacement and other metrics as in Jeuland and Pattanayak (2012). A better understanding of the multiple functions of the traditional fire, including valued light output and space heating output and the effects of a reduction in these, is needed in order to more accurately predict outcomes of this significant consideration. The process of gathering this ethnographic and field-specific data can help implementers to better understand the needs in the community before choosing a strategy. A database of disaggregated needs and input values in different communities can be developed.

The model contains the algorithms required for life cycle analysis but does not yet include the data due to the specific supply and transport information required, nor does it include the impact or costs of overhead and implementation. Expansion of the model to include forecasting out 20-30 years given progressive displacement fractions and rates of growth is a potentially useful addition. In addition, analysis can be extended to consider the inverse questions of determining optimal solutions that meet a given outcome target, such as limiting carbon emissions or forest harvest rate. Finally, future work will include development of the model into a web tool where users can select from new or defined technologies, input local data, and draw from databases of relevant parameters in order to make decisions specific to their target communities.

Resources to develop and disseminate clean energy service technologies are limited, but the need is great. As a result, the use of systems modeling tools to predict outcomes of technologies introduced into a community can help to more efficiently develop strategies that are ultimately more effective and sustainable, such as the integrated strategy developed here. It is hoped that the concepts in this work can be used to more holistically approach the design of energy service programs in order to develop strategies tailored to the specific local needs as well as socioeconomic and cultural conditions. Although applied in the context of rural communities in developing countries in this study, this framework may have applications in industrialized nations as well where energy supply will likely be transitioning from centralized electricity grids to a more localized and distributed system during the coming decades.

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