An integrated systems model for energy services in rural developing communities

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ABSTRACT

This paper develops a systems-based integrated model for investigating the impacts of various energy technologies as applied to meet specific energy needs in a rural developing village. The model enables the designer to examine of a variety of energy technology components subject to local and global constraints and reports the outcomes in terms of multiple objectives including energy consumption, climate effects, health impacts, cost analyses, and social considerations. It enables accounting for important application factors such as usability, multi-functionality, stacking and incomplete displacement of traditional methods, opportunity costs, effective discount rates, and impact to quality of life. Use of the model to analyze the baseline case of a well-characterized village in Mali revealed the conflicts between social, economic, and environmental objectives that often exist between stakeholders, highlighting the importance of attention to consumer preference. Analysis based on disaggregated energy needs illustrated that often the relative impacts between energy strategies are not immediately evident, suggesting that

holistic systems-level analyses are critical before selecting a specific strategy to supply improved energy services to households in a community.

KEYWORDS

Integrated energy systems modeling; household energy; climate; health; biomass cookstoves; solar

NOMENCLATURE

<i>AC</i>	annual cost
<i>AED</i>	annual energy delivered
<i>AEE</i>	annual embodied energy
<i>AEI</i>	annual energy of implementation
<i>AEU</i>	annual energy use
<i>AH</i>	annual hours
<i>AHR</i>	annual forest harvest rate
<i>AQG</i>	air quality guideline
<i>C</i>	cost
cap	capita
<i>EAC</i>	equivalent annual cost
<i>EE</i>	embodied energy
<i>EF</i>	emission factor, energy basis
<i>ef</i>	emission factor, mass basis
<i>f</i>	fraction
<i>GWC</i>	global warming commitment
<i>GWP</i>	global warming potential
<i>i</i>	iteration counter
<i>L</i>	lighting output
<i>LHV</i>	lower heating value
<i>m</i>	mass
<i>N</i>	quantity
<i>Q</i>	firepower
<i>Quality</i>	quality of life metric
<i>r</i>	discount rate
<i>RHI</i>	relative hazard index
<i>T</i>	years
<i>VH</i>	valued hours (lighting)
<i>w</i>	weight

x	variable
y	output; impact
β	fuel price elasticity
η	efficiency

subscripts

<i>as-rec'd</i>	as-received
<i>base</i>	baseline
<i>cap</i>	capacity
<i>capital</i>	capital
<i>coll</i>	collected fuel
<i>cook</i>	cooking
<i>dis</i>	displacement
<i>elec</i>	electricity
<i>energy</i>	human caloric energy
<i>fuel</i>	fuel type
<i>HH</i>	households in the village
<i>heating</i>	space heating
<i>i</i>	use index
<i>imp</i>	implementer
<i>j</i>	device index
<i>k</i>	emission species index
<i>l</i>	material index
<i>labor</i>	human labor
<i>light</i>	lighting
<i>LCA</i>	life cycle analysis
<i>m</i>	quality of life index
<i>maint</i>	maintenance
<i>mech</i>	mechanical
<i>NRB</i>	nonrenewable
<i>operating</i>	operating
<i>post</i>	after intervention
<i>pre</i>	before intervention
<i>prep</i>	fuel preparation
<i>reb</i>	rebound
<i>shadow</i>	shadow value of time
<i>subsidy</i>	subsidy
<i>time</i>	fuel collection time
<i>TSF</i>	three-stone fire
<i>useful</i>	useful lifetime
<i>unv</i>	unvented

1. INTRODUCTION

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 (IEA, 2010; DFID, 2002, Johnson and Bryden, 2012). Although this traditional method is flexible, free, and familiar; its continuing use for hours each day in hundreds of millions of rural households is detrimental in a number of ways. The indoor and outdoor air pollution from the pervasive use of these fires creates significant respiratory and circulatory complications in both children and adults, the results of which represent the fourth leading cause of death worldwide (Lim et al., 2012). Residential biomass combustion is estimated to be responsible for 25% of the global black carbon emissions, a pollutant approximately 910 times stronger than carbon dioxide which creates serious impacts on the climate and accelerates glacial melting (Bond et al., 2013). And the collection and use of biomass fuel, especially in areas with retreating forests, takes time and energy, and creates drudgery and safety concerns. The use of open fires also poses safety risks to users and children, who are often in the kitchen alongside the cook.

Improving access to clean energy services can facilitate improved health and livelihoods and serve as a precursor to other economic and social development (Gaye, 2007). Yet within these diverse, complex, and highly-localized communities, the most effective strategies to provide clean energy to meet basic needs for thermal energy are not clear, and success of programs to provide cleaner technologies such as biomass cookstoves or subsidize clean fuels such as LPG or electricity has often been limited (Madubansi and Shackleton, 2006). Often 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 (Fig. 1). Within a community energy ecosystem exists a range of technical, economic,

social, and environmental objectives that can conflict between these scales creating an imbalance between stakeholders. Because of this the outcomes of an energy intervention can vary widely based on technology design choices and local conditions. As a result, development of an effective solution requires a clear understanding of the direct and indirect impacts of design choices that are rooted in the fundamental interactions between energy, the environment, and society.

Figure 1. Factors in the village energy system

This paper develops a systems based model that considers local energy needs, demographics, fuels, and devices and enables the user to examine the outcomes of various energy interventions in terms of a range of technical, environmental, economic, and social outcomes.

2. BACKGROUND

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). 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 (Heltberg, 2005; Pachauri and Jiang, 2008; Eckholm et al. 2010; San et al., 2012). In particular, Johnson and Bryden (2012) examined disaggregation of energy use in a rural off-grid village in Mali. They found that energy used in the household to meet basic needs represents 92% of the energy use in the village, a level similar to that in many rural developing communities (Bhandari and Stadler, 2011).

In the Johnson and Bryden (2012) study, 96% of the energy used was thermal energy, or heat for cooking processes (54%), bathing and washing (20%) and space heating (17%). Cooking includes boiling and frying, roasting nuts and rendering oil, making medicine, preparing feed for livestock, steeping tea, seasonal traditions, and baking bread. Space heating is needed on a seasonal and regional basis. Indoor and outdoor lighting are critical energy needs. Disposable batteries for flashlights and other small devices provide a negligible amount of energy, yet often represent the most costly energy expenditure in households (Johnson and Bryden, 2012). Beyond the residential sector, the commercial sector in a rural developing community typically includes artisanal activities (e.g., 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, 2012; 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.

It was found that 94% of the energy services in this community were provided by three-stone fires. In the home, the traditional fire is able to simultaneously provide 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 Wingebach, 2014; San et al., 2012). The three-stone fire is free 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 village energy alternatives introduced.

Although electrification of rural villages is an important and ongoing goal, electricity can not adequately meet all rural energy needs even in areas that are connected to the grid. The inadequate amperage, high cost, and unreliability of electricity makes it unsuitable for thermal tasks in these communities. Recent estimates indicate there are 1.4 billion people without electricity, yet 2.7 billion people cook and heat with biomass (IEA, 2010), suggesting that roughly 1.3 billion people have access to electricity but do not use it for thermal energy. This is supported by studies by Madubansi and Shackleton (2006) and others that found no significant decrease in fuelwood consumption after village electrification. 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.

A successful intervention needs to address the constraints within the village energy system, which include the specific energy needs, the available fuels, and socio-economic considerations. This requires evaluation of the performance of a technological component given its characteristics, including usability, multi-functionality, efficiency, emissions, durability, cost, safety etc. And so the goal of this model is to allow for investigation of the functionality of various technological components when applied within a particular village setting.

There are a number of potential components available for inclusion in a village energy system, including devices, fuels, and changes in practice. Some of these components are shown in Fig. 2, although the list is by no means exhaustive. As shown, components can include devices, fuels, and practice. Devices can include different types of biomass cookstoves, lighting systems, water pumps, and more. Fuel components include the available biomass, processed biofuels, and fossil fuels. And changes in practice, such as using embers to ignite fires more quickly or cooking with added ventilation, are also an option that can be implemented through education and outreach activities.

THERMAL			LUMINOUS	MECHANICAL
			Lighting	Mechanical
Cooking	Space Heating	Water Heating		
<div>Practice</div> <ul style="list-style-type: none"> • Three-stone fire • Embers Ignition • Ventilation • Communal • Water preheating <div>Device</div> <ul style="list-style-type: none"> • Cookstoves • Shielded fire • Gasifier • Fan • Tier 1-4 • Chimney • Charcoal • Kerosene <div>Fuel</div> <ul style="list-style-type: none"> • LPG • Solar • Biogas system • Liquid biofuels • Electric 	<ul style="list-style-type: none"> • Three-stone fire • Biomass heating stove • LPG heating stove • Electric heating stove 	<ul style="list-style-type: none"> • Three-stone fire • Solar water heater • Any cooking device 	<ul style="list-style-type: none"> • Three-stone fire • Kerosene wick • Pressurized Kerosene • Candles • Solar lanterns • Incandescent, fluorescent tube, CFL or LED bulbs, electrically powered 	<ul style="list-style-type: none"> • Grinder • Motorcycle • Electric scooter • Water pump • Tractor

Figure 2 Potential components

The goals of a village energy system are to provide access to non-polluting, affordable energy services that are effective from the viewpoint of the user. More specifically, these goals need to include quantifiable measures of the following:

- 1) Minimization of energy consumption, especially that which is non-renewable, with maximization of useful energy delivered and the services provided
- 2) A decrease in environmental impacts 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 and a reduction in forest harvest rate
- 3) A reduction of health impacts by lowering human exposure to harmful pollutants such as carbon monoxide (CO) and fine particulate matter (PM_{2.5})

- 4) A minimization of costs, both financial and opportunity, upfront and ongoing, to both the user and implementer in terms of an annual investment over the lifetime of the technology as well as the relative incremental costs of other impacts (i.e., cost per ton of carbon reduction).
- 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

A model is needed that links the various pieces of a village energy system together and then examines the performance of this system in a particular village setting. These pieces include the needs for energy services, the technologies and fuels available, and the goals of the users. Recognizing that ultimately the performance of a technology depends on a broad range of factors, linking these pieces provides the ability to simulate the impacts of design choices for components such as improvements to efficiency or usability, changes in parameters such as fuel subsidies, and differences in outcomes between communities. This allows the designer to answer a set of questions for a specific village setting, and to optimize the discrete pieces of the system in the context of all the other relevant areas.

3. ENERGY SYSTEMS MODELING

A variety of models have been used to examine 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. However, as shown in Table 1, there are a variety of existing models that cover areas within the energy types, analysis goals, factors involved, and objectives in part needed to model rural village energy systems. The models in Table 1 are divided into three 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, and (c) multi-criteria decision analysis applied to given scenarios. 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.

Table 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	Stakeholders	Participation	Energy Eff.	Economic	Environment	Health	Social	Institutions	Equity
<u>Energy Modeling Packages</u>																												
Paleta, 2012	HOME R		x	x						x	x									x	x							
Johnson, 2013	HOME R			x		x	x			x										x	x							
Mustonen, 2010	LEAP					x														x	x	x						
Limmeec hokchai, 2007	LEAP, AHP,C BA	x		x		x		x	x	x	x							x		x	x	x		x				
Howells, 2005	MARK AL	x	x	x			x				x	x								x	x	x						
Ekholm, 2010	MESS AGE	x					x	x			x			x			x					x				x		
Byrne, 1998; 2007	RREA D		x			x		x			x									x	x			x		x		

<u>Conceptual Frameworks for Rural Energy</u>																			
Cherni, 2007	ITDG+ SURE DSS		x			x								x	x	x		x	x
Henao, 2012	SURE-DSS		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	
Georgoulou, 1997	ELECTRE III		x			x			x	x	x			x	x	x		x	
Silva, 2009	GP		x			x			x		x			x	x	x		x	
Ramanathan 1994	GP	x				x			x	x	x			x	x	x		x	
Ramanathan 1995	AHP-GP			x			x						x		x	x		x	
Beccali, 1998	Fuzzy+ ELECTRE	x	x	x			x			x	x			x	x	x		x	

[illegible]

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). Of these, the LEAP, META-Net, MARKAL, MESSAGE, RREAD and HOMER models 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). The LEAP model can examine 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. 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. 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 in terms of the Millennium Development Goals. The latter two scenarios assumed adoption of improved cookstoves by 48% and 86% of electrified households, respectively. Their study qualitatively discussed the effects of rural electricity generation scenarios on income and public services 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.

- Kanagawa and Nakata (2007) used the bottom-up ‘META-Net’ economic modeling system jointly developed by Lawrence Livermore National Laboratory and Tohoku University to forecast health and economic impacts of wood versus gas cooking in India, including 5 end-uses, 28 devices, and 7 markets as inputs. The model included the opportunity cost of fuelwood collection. 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 the TIMES model 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 given a range of inputs to generate electricity (renewable, converted, and imported).
- 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 to forecast national energy consumption by type (i.e., 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.

- 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) included lifecycle analysis, socioeconomic assessment with logit modeling to determine market potential, GIS classification, and livelihoods assessment.
- 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; Johnson, Glassmire, and Lilienthal, 2013).

While each of these models has significant strengths none of them individually addresses the set of issues of concern here. That is, how to develop a comprehensive systems model of village energy that addresses detailed thermal and electrical generation with analysis of application-relevant factors such as usability, functionality, rebound, stacking and the characteristics desired from the perspective of the user such as convenience, desirability, and safety.

3.2 Conceptual Frameworks

Several conceptual frameworks of village development systems have been introduced to analyze a broad picture of the effects of energy development efforts while considering the objectives, stakeholders, needs, and constraints specific to a village system. For example, Practical Action developed “Energy for Rural Livelihoods: A Framework for Sustainable Decision Making” (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 multi-criteria decision modeling software package Sustainable Rural Energy Decision-Support System (SURE-DSS) was developed based in part upon this framework and includes a comprehensive assessment of local and regional conditions prior to the introduction of energy systems. The analysis assesses strengths and weaknesses of a community in terms of the five types of assets and then seeks to optimize impacts on each by minimizing the qualitative distance from the “ideal” level (Brent and Kruger, 2009; Cherni, 2005; Cherni et al., 2007).

3.3 Multi-Criteria Decision Analysis

Various multi-criteria decision analysis methodologies have been used to analyze several aspects of energy services in developing communities. Cost-benefit analysis (CBA) monetizes outcomes of various objectives and comparing cost effectiveness in terms of device, fuel and implementation costs, and cost per household of potential scenarios (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).

The analytical hierarchy process (AHP) pair-wise comparison is used to prioritize alternatives associated with objectives, and goal programming (GP) seeks to minimize the deviations from set goals for objectives. 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. Silva and Nakata (2009) used GP for optimization of rural electrification with renewable energy systems in Columbia with four goals and four priority structures

Fuzzy programming and the ELECTRE method family has been used to account for uncertainty, the qualitative nature of some indices, and weighting for multiple objectives (Georgopoulou, Lalas and Papagiannakis, 1997; Beccali, Cellura, and Ardente, 1998). Beccali, Cellura, and Ardente (1998) used indifference, strict preference, and veto thresholds to consider 14 different technologies/energy sources for thermal and electrical energy generation 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 compare energy sources allocations for cooking and heating energy with uncertainty to optimize the objectives of cost, emissions, social acceptance, and utilization of local resources.

3.4 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 aspects that are needed for the selection of energy technologies for a given village. These include

- Flexibility to analyze 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, a comprehensive, multi-actor, multi-objective model that allows for investigation of an 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.

4. QUANTIFICATION OF IMPACTS

To evaluate the multiple objectives and impacts on village energy individually, each must be quantified in an understandable way. While assigning monetary benefits to users or representing as economic externalities factors such as health, carbon, and time for optimization purposes is possible; it is not always preferred for several reasons. First, it can lead to overestimation of the actual benefits because direct financial benefits to the household do not automatically result from improvements to health or climate (Mink, 2010). Second, the current cost of carbon fluctuates with the market rate and does not 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. Because of this, in this paper the quantification of specific impacts to environment, health, energy consumption and other outcomes are developed based on the literature.

4.1 Environmental impacts

Environmental effects are most commonly reported in terms of greenhouse gas emissions as tons of carbon dioxide equivalent ($\text{tCO}_{2\text{e}}$). 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. 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, Rehfuss 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 2, the weighting of many of the products of incomplete combustion is heavier in the shorter time scale than the longer.

Table 2. Global warming potential

Emission	GWP ₂₀	GWP ₁₀₀
CO ₂	1	1
CH ₄	72 ^a	25 ^a
N ₂ O	289 ^a	298 ^a
CO	10 ^b	1.9 ^a
NMHC	4.9 ^b	3.4 ^a
BC	3200 ^c	910 ^c
OC	-250 ^b	-75 ^b

^aForester et al., 2007; ^bBond, Venkataraman, and Masera 2004; ^cBond 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, Rehfuss, and Tediosi (2007) and Jeuland and Pattanayak, (2012), calculated as the replacement cost and market value of the trees, respectively.

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.

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 subsidies. 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.

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, 2012) 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).

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 Velthuisen (2000), is predicted using measures of efficiency improvement, $\Delta\eta$, and the energy cost (price) elasticity of demand for energy services, β :

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

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 Fig. 4.

Figure 3. 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. 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 (Dufournaud, 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. Income and Fuel Price Elasticities

Study	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

^aIn Zein-Elabdin, 1997, ^bIn Cuthbert, 1998

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.

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.

5. MODEL DEVELOPMENT

A high level diagram of an integrated systems model for village energy system addressing the needs identified above is shown in Fig. 5. The inputs to the model include 1) the strategy selected by the designer in terms of which technologies are applied; and 2) the characteristics of the technological components and the local and global energy needs, available fuels, and other variables available in databases. The outcomes resulting from these inputs are analyzed within the model and are dependent on a number of design, application, and adoption

processes that occur within the system. These dictate how the technology is used (application) and the level of expected consumer acceptance dictating how much it is used (adoption). These are analyzed numerically through a series of sub-models. The outcomes are quantified 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.

Figure 4. The village energy system model

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 five databases: (a) the annual magnitude of each energy use and whether that task is conducted on a scale from outdoors to indoors, 0 to 1, or; (b) technology performance expected in the village including efficiency, emissions, economic, lifespan, and social acceptance metrics; (c) fuels including the local lower heating

value, cost to purchase, collection time, and harvest nonrenewability factors; and (d) local variables such as labor rate, shadow value, population, and number of cooks. In addition, there is (e) a global database of constants such as global warming potentials and indoor air quality guidelines.

As shown in Fig. 6, the model operates first by generating an input file from the databases, 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.

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.

$$x[iteration] = distribution(average(x), deviation(x)) \quad (2)$$

During the first run of the model, the baseline scenario data must be initialized. This is achieved 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 5. Flow chart for the model

5.1 The input file

Fig. 7 shows the operations to create the input file. 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 collected in a database and run through progressively.

Figure 6. Development of the input file

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 to determine the baseline impacts, if the displacement fraction of the new technology is less than 1, the fraction remaining undisplaced is included in the total impact for each energy use (y_i) which

includes the sum of the impact of the new technology ($y_{i,j}$) applied to the energy need and the remaining fraction undisplaced ($1-f_{dis,i,j}$) assigned to the baseline values ($y_{i,base}$).

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

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 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.

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

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

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, $Q_{kerosene}$.

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.

5.2 The energy need sub-model

As shown in Fig. 8, 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 (Eq. 1), which is measured as the fraction of energy savings retaken by increased demand.

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.

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

Figure 7. The energy need sub-model

5.2.1. 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).

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

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

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

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 output of that light (L_{light}) is determined from the lighting efficacy, η_{light} , in lm/W 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 lm/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 lm. 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 A·h, or 1200 W·h 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 lm/W (Sloan, Bryden, and McCorkle, 2012). This equates to 1.9 hours of light per household per day at a level of 1,575 lm.

$$L_{light,i,j} = \eta_{light,j} Q_j \quad (10)$$

$$AH_{light} = \sum_i \sum_j H_{light,i,j} \quad (11)$$

It is assumed that the lighting efficacy of the three-stone fire is comparable to that of an unpressurized kerosene lantern, and an unpressurized 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 sufficient for activities such as education and productive activities (e.g., cash producing artisanal crafts) to be conducted, these hours of lighting are valued

separately from the low-level light produced by kerosene or firelight. Specifically in the study, these valued hours (VH_{light}) are tallied when greater than 500 lm ($L_{threshold} > 500$ lm).

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

In addition, the forest harvest rate is tracked by monitoring the use of fuelwood-based energy to allow for analysis of fuel harvest renewability.

$$AEU_{fuelwood} = \sum_i AEU_{fuelwood,i} + \frac{1}{\eta_{charproduction}} \sum_i AEU_{charcoal,i} \quad (13)$$

$$AHR_{fuelwood} = \frac{AEU_{fuelwood}}{LHV_{fuelwood,as-rec'd}} \quad (14)$$

5.2.2 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 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 (Table 2). 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.

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

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.

5.2.3 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 well 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 $35 \mu\text{g}/\text{m}^3$ for the “interim target 1” and $25 \mu\text{g}/\text{m}^3$ for the “interim target 2” and overall value for $\text{PM}_{2.5}$ averaged over 24 hours (WHO, 2006), and $7 \text{ mg}/\text{m}^3$ 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.

$$RHI_{i,j,k} = \frac{f_{unv,i} EF_{j,k} AEU_{i,j}}{AQG_k} \cdot \frac{1}{365} \quad (16)$$

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) .

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

5.2.4 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 $f_{coll,fuel}$.

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

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 (Johnson and Bryden, 2012). 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.

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

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} .

$$AC_{time} = f_{shadow} C_{labor} AH_{fuel} \quad (20)$$

For example in the Malian village, researchers 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, 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.

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

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

$$AC_{operating} = AC_{fuel} + AC_{time} + AC_{light} \quad (22)$$

5.2.5 Social

Regardless of the potential performance of a technology, benefits will not be realized if there is no motivation for adoption or there is not 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 the fabric of 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 to 0.25 for each by default.

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

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.

5.3 The component 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 (Fig. 9).

Figure 8. The component sub-model

5.3.1 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 the total quantity of devices that would be needed in the village (N_i) for that energy strategy. N_i is equal to (a) the number of cooks in the case of cooking 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, $f_{dis,i,j}$.

$$N_j = f_{dis,i,j} N_i \quad (24)$$

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.

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

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

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.

$$AC_{maint} = \sum_j N_j C_{maint,j} \quad (27)$$

5.3.2 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).

$$AEE = \sum_j \frac{N_j EE_j}{T_{useful,j}} \quad (28)$$

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.

$$GWC_{LCA} = \sum_j N_j \sum_k \sum_l m_{j,k,l} \cdot ef_{k,l} \cdot GWP_k \quad (29)$$

5.4 The output file

Finally, the impacts for each energy need and technology are totaled and passed on to create the output file (Fig. 10). 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.

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

$$EAC_{total,user} = AC_{operating} + EAC_{capital,user} + AC_{maint} \quad (31)$$

$$EAC_{total,implementer} = EAC_{capital,implementer} + AC_{implementation} \quad (32)$$

$$EAC_{total} = EAC_{total,user} + EAC_{total,implementer} \quad (33)$$

Costs are then analyzed in three ways, the payback time through fuel and time savings, the levelized cost of energy ($LCOE$), and the fraction of household income (f_{income}). To compute the average fraction of household income in the village spent on energy services, the annual income per household is assumed as one member employed at the going labor rate for 40 hours per week 4 weeks per month. This fraction is an illustrative metric for scenario comparison.

Figure 9. Flow chart illustrating the development of the output file

$$T_{payback} = \frac{\sum_j N_j C_{purchase,j}}{(AC_{fuel} + AC_{time})_{base} - (AC_{fuel} + AC_{time})_{post}} \quad (34)$$

$$LCOE = \frac{\sum_{t=1}^n \left[\frac{\sum_j (N_j C_{purchase,j,t} + N_j C_{maint,j,t}) + AC_{fuel} + AC_{time}}{(1+r)^t} \right]}{\sum_{t=1}^n \frac{\sum_i AED_i}{(1+r)^t}} \quad (35)$$

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

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

$$C_{climate} = \frac{EAC_{total}}{GWC_{total}} \quad (37)$$

$$C_{health} = \frac{EAC_{total}}{RHI} \quad (38)$$

The cost of greenhouse gas savings can be compared to the market value for carbon offsets, C_{CO2e} .

6. CASE STUDY

To illustrate the application of the model, a well-characterized village in Mali studied by Johnson and Bryden (2012) is considered. In this village of 770 residents located in the Sahel, the transition region between the Sahara desert and the forests of mid-continent of Africa, energy use was quantified in the village on an annual basis through extensive measurements during various seasons. It was found that energy for the household represented 92% of total energy use in the village. Of this, the specific end uses are shown in Table 4.

Table 4. Household energy uses in the Malian Village (Johnson and Bryden, 2012)

Use	Device	Fuel type	Energy Use (GJ/y)	Fraction
Cooking	cookstoves	wood	2,230	51%
Water heating	cookstoves	wood	947	22%
Peanut roasting	cookstoves	wood	106	2%
Tea steeping	tea stove	charcoal	49	1%
Space heating	heating fire	wood	814	19%
Shea processing	cookstoves	wood	117	3%
Medicine making	cookstoves	wood	56	1%
Lighting	kerosene lantern	kerosene	17	0%
Lighting	fluorescent bulbs	solar/battery	3	0%
			4,339	

These services, categorized as cooking, specialty cooking (including peanut roasting, tea steeping, shea processing, and medicine making), water heating, space heating, and lighting; are provided by the technologies (Table 5) and fuels (Table 6) indicated. Note that since the solar lighting system was installed by the researchers and reported to have displaced half of the kerosene used for lighting, the analysis by the model considers the impact prior to that installation.

Table 5. Performance of Technologies -- Thermal Efficiency (%) and Emission Factors (EF) (g/MJ) with pooled standard deviation from the literature

	Therm. Eff.	EFCO2	EFCH4	EFN2O	EFCO	EFNMHC	EFBC	EFOC	EFPM	Source
Three Stone Fire	0.1604 ± 0.02	101.9 ± 11.5	0.235 ± 0.124	0.012 ± 0.009	5.162 ± 1.339	0.458 ± 0.332	0.073 ± 0.036	0.169 ± 0.072	0.319 ± 0.091	a-q
Charcoal Tea Stove	0.244 ± 0.08	100 ± 8.13	0.488 ± 0.092	0.006 ± 0	9.364 ± 1.852	0.514 ± 0.141	0.037 ± N/D	0.097 ± N/D	0.072 ± 0.04	a-c,e,g,k,m,o-r
Heating Fire	-- ± --	100 ± N/D	0.47 ± N/D	0 ± N/D	8.784 ± N/D	0 ± N/D	0 ± N/D	0 ± N/D	1.419 ± N/D	s
Kerosene Lantern	-- ± --	71.9 ± 0	0.01 ± 0	0 6E-04 ± 0	0.404 ± 0.041	N/D ± N/D	2.334 ± 3.083	0.082 ± 0.085	2.459 ± 0.505	t-v

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., 2009; l Roden et al., 2008; 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 Smith et al., 1993; s Bhattacharya, 2000; t Bond et al., 2004; u Forester et al., 2007; v Lam et al., 2012

Table 6. Fuels

Name	LHV (MJ/kg)	Cost (\$US/GJ)	Time (hr/GJ)	fNRB
Wood	14.8 ^a	0	9.3 ^a	0.73 ^b
Saved Charcoal	29.7 ^a	0	0	0.73 ^b
Kerosene	43.3 ^d	25 ^e	0	1

a Johnson and Bryden, 2012a; b CDM, 2010; c Cuthbert and Dufournaud, 1998; d Grieshop, Marshall, and Kandlikar, 2011; e World Bank, 2001

The average labor rate in the village is that of unskilled labor at approximately \$2 per day according to observations of the author. 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) in this village, as it has been observed that there are labor opportunities for weaving baskets to sell at the market in Bamako accessible by bus from the village.

Fig. 10 shows the estimated contributions of the various energy uses to the overall energy consumption, climate, health, and economic impacts in the baseline scenario. Such an analysis illustrates an important question of which end uses to target given a set of objectives and potential components.

Baseline

Figure 10. Analysis of the baseline scenario in terms of (A) 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)

As shown in Table 4, 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 operating cost, however, lighting represents nearly 20% of total energy expenditures in the household when the opportunity cost of time spent collecting fuelwood is included. This 20% represents the only monetary outlay due to the purchase of commercial kerosene and therefore is likely identified as the most significant

expense in the viewpoint of the user. 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 important consideration from the point of the user illustrates why, when the researchers came to the village, the users identified their desire was for lighting as opposed to technologies that would address the need for other energy services such as cooking. Note that these figures do 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, 2012).

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). Note that the climate impacts include Kyoto and non-Kyoto species on a 100-year timeframe, and black carbon has the highest global warming potential of all of the emission species (Table 2). Cooking, water heating, and space heating continue to contribute their proportional share to climate impacts relative to their energy consumption since they are all conducted with the three-stone fire.

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, on the other hand, are minimal due to the high level of ventilation applied when typically heating water outdoors.

This analysis of the baseline scenario illustrates the conflicting objectives that represent a significant challenge for village energy programs. For example, it appears that cooking would be the energy service 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 at night that reduce or eliminate household air pollution would provide the largest impact on health given the assumptions used.

7. CONCLUSIONS AND FUTURE WORK

The model developed here sought to address the limitations of previous models of energy systems as applied to rural developing communities. This model analyzes the comprehensive range of objectives simultaneously, including technical, environmental, health, and economic metrics. It also incorporates use-related factors such as usability, multi-functionality, stacking, and incomplete displacement of technologies; as well as aspects important to the user including opportunity costs, effective discount rates, and impact to quality of life. Analyses are based on disaggregated measures of energy applications across the village and are useful to assess the impacts at an annual, community scale, as opposed to a limited task-by-task comparison as is often the subject of field studies and predictions. With this model, it is possible to compare technologies, design choices, and policies anywhere from the scale of technology to the global scales and optimize those discrete pieces within the context of the larger system. Cost-benefit analysis, optimization, forecasting, and trade-off analysis can be conducted and design choices

can be better informed early in the design phase. The most significant limitation of the present work, and energy interventions in general, is in understanding and predicting the rates of adoption of the new technologies and displacement of the traditional technology.

These complications are seen through the case study, which identified how differing end uses contribute differently to the various objectives for efficiency, health, environment, and operating expense. While the various stakeholders share similar goals, the relative importance of each of these objectives may differ. Because of this it is challenging to determine which energy service to target when providing improved technologies. Pairing these conflicting objectives with technologies that offer relative conflicts with efficiency, emissions, cost and attractiveness to the user in terms of usability and convenience, the optimal strategies are not apparent.

Future work will include increasing the fidelity and application of the model. While the present model incorporates straightforward equations for the various outcomes, more detailed models of aspects such as health impacts, consumer choice, rebound, and forest renewability will be developed and integrated into the model. Results of the model will be validated using in-field measurements, and the application of the model will be expanded to a variety of communities and technologies.

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