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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.

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 [29,52,60]. 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 [74]. 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 [15]. 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 [40]. 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 [80]. 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.

This paper develops a systems based model that considers local

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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
T	years
VH	valued hours (lighting)
w	weight
x	variable
y	output; impact
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

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.

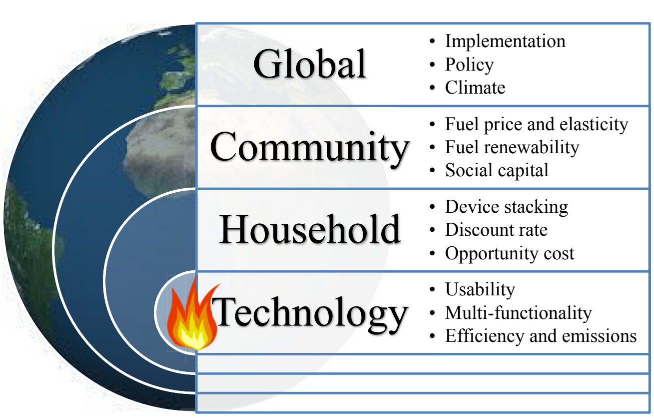

Fig. 1. Factors in the village energy system.

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 [29]. 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 [34,46,91,101]. In particular Johnson and Bryden [60], 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 [10].

In the Johnson and Bryden [60] 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