Modeling the Dynamics of the Energy, Environment, & Poverty Nexus: A Study of Biogas Unit Diffusion in Andhra Pradesh, India

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Abstract

In this paper, we use system dynamics modeling to examine the broad set of socio-economic and ecological factors which together play a role in determining a household's decision to adopt a biogas unit. Informed by data we collected during the summer of 2008 with the Foundation for Ecological Security (FES) in Andhra Pradesh, India, and with corroboration from the relevant technology diffusion and energy transition literature, we model the process of biogas adoption and traditional technology replacement. We find that only by improving biogas interventions to address this complex interplay of energy, environment, and poverty-related factors, notably household usage of a multiple-stove strategy and the energy insecurity of the poorest households, can an intervention realize desired human and ecological outcomes. We conclude with a discussion of model applications for both FES and the broader rural development community.

Key words: *adoption, biogas unit, energy insecurity, energy transition, household decision-making, technology diffusion*

Introduction

Biomass in the form of fuelwood, agricultural residue, and animal waste is among the most prevalent sources of energy in India, South Asia, and indeed throughout the developing world. Combustion of biomass has adverse impacts on public health, economic development, and local ecology. Approximately 2.5 billion people globally depend on biomass to meet everyday needs like cooking and heating (International Energy Agency, 2000). In India alone, 2 billion kilograms of biomass are burned every day, accounting for 90% of rural energy consumption (Balakrishnan, 2002). Biomass combustion is responsible for a significant proportion of carbonaceous aerosol emissions and "brown clouds" over the subcontinent (Gustafson et al, 2009). Likewise, emissions from biomass combustion contain dangerous levels of fine particulate matter (PM2.5, PM10), carbon monoxide (CO) and nitrogen oxides, causing life-threatening and debilitating illnesses in its users, especially poor women and children (Smith, 2000). The extraction of fuelwood from forests is among the most significant, on-going drivers of deforestation in South Asia as well (Kohlin and Parks, 2001). This dependence drives fuelwood scarcity and increases the opportunity costs due to additional time spent collecting fuelwood (Barnes, et al, 1994; Amacher, Hyde, Kanel, 1996). The continuing dependence on biomass as a primary energy source has devastating effects on both human and natural systems.

To reduce these negative effects, governments and nongovernmental organizations (NGOs) throughout the developing world have under-taken interventions to disperse improved combustion technologies that would require less fuel, reduce dangerous emissions, and yet meet the energy needs of rural households. Although these more efficient and emissions-reducing technologies can be produced in the laboratory, designing them to meet the needs of users in various socio-cultural contexts has proved challenging. Improved combustion technology programs have often been unsuccessful in that households a) do not adopt the improved technologies at all, or, b) if they do adopt, use them in a way that does not achieve the sought after level of reductions in fuelwood used and harmful emissions (Barnes, et al, 1994). Adoption in this context refers to the household decision to acquire new combustion technology, while implementation refers to the household's actual use of the new combustion technology (Klein & Knight, 2005). Hence, the challenge of ensuring successful uptake and proper use of improved combustion technologies in rural households stems from the twin failures of adoption and implementation.

The failure of these interventions stems from a misunderstanding of household decision-making processes around improved combustion technology adoption, which are grounded in the livelihoods of the rural poor: the social, political, cultural, economic, and ecological dimensions of energy security, as well as access to alternative sources of energy and household strategies to meet fluctuating energy supply and demand (Barnes, et al, 1994; Hiemstra-van der Horst & Hovorka, 2008; Masera et al, 2000). We need substantial advancement in our understanding of energy transition and innovation adoption and implementation to effectively transform the policy and practice models that drive government and NGO approaches to adoption and implementation of alternative energy technologies (Hiemstra-van der Horst & Hovorka, 2008).

The Foundation for Ecological Security (FES) has been disseminating biogas units – a combined stove and alternative energy production technology - since 2000 in the revenue villages of Thamballapalle and Kalicherla in the Papagni River Basin of Chittoor District in Andhra Pradesh. This paper presents a qualitative model of the inter-linkages between energy, environment, and poverty that drive the uptake of an improved combustion technology intervention. This model is based on data from a household survey, informal interviews, and direct observations obtained from a study of household energy transition and combustion technology use carried out in Andhra Pradesh, India during the summer of 2008. In seeking to understand these dynamics, our ultimate goal is to enable sustained implementation of biogas units within the target area.

Background and Observations from the Field

Data for this study come from households in Thamballapalle and Kalicherla Revenue Villages in the Papagni river basin of Chittoor district in the state of Andhra Pradesh, India. Households in this area are highly dependent on biomass for their daily needs and livelihoods, specifically wood for fuel and timber, fodder for cattle, and non-timber forest products (NTFPs) for income and food. Many hamlets in the revenue villages of Thamballapalle and Kalicherla depend on the Sadhukonda Reserve Forest (RF) (lat 13° 46' 21.87" and 13° 54' 35.15" N; long 78° 25' 13.57" and 78° 32' 13.15" E)[1] (FES, 2003). Sadhukonda RF is a 6,331 ha reserve of tropical mixed dry deciduous forest and thorny scrub located at the nexus of the Deccan plateau and the Eastern Ghats in southwestern Andhra Pradesh. Altitude ranges between 470-1128 m above sea level and the reserve has an average annual rainfall of 650 mm. According to 2003 data, collected by FES, on the energy demand of local hamlets, households in the Revenue Village of Kalicherla extract 8,434 metric tons (mt) of fuelwood from Sadhukonda RF per year and households in Thamballapalle extract 6,769 mt per year. *Erythroxylon monogynum, Plectronia parviflora, Chomelia asiatica, Lantana camara, Randia dumetorum, Ixora parviflora,*

1 Ecological data on the Sadhukonda Reserve Forest is obtained from FES's Working Paper No. 9: *Biomass assessment in Sudhukonda Reserve Forest and adjoining areas, Madanapalle, Andhra Pradesh, India*

Flacourtia sepiaria, and *Cassia auriculata* are species commonly used for fuelwood in the Sadukhonda RF. Households in hamlets near the Sadhukonda RF depend on the forest much more than households from hamlets that are farther away. These households rely more heavily upon nearby wastelands for their fuelwood needs. Consistent with energy trends throughout the developing world, poor households in this region depend more on common pool resources - forests and wastelands - for fuelwood than do middle and upper income households.

Energy insecurity is widespread among poor households in this region. By energy insecurity, we mean the inability of households to secure adequate sources of energy to meet their daily needs at a reasonable cost. Studies from a variety of contexts have shown that community forestry programs can reduce access to fuelwood among the poor by creating restrictive extraction policies for common lands (Agarwal, 2001), and there is evidence that this is the case in Andhra Pradesh (Reddy et al, 2006). Forests in close proximity to communities and wastelands are often managed under Andhra Pradesh's community forestry management (CFM) program, a response to India's 1988 National Forest Policy to decentralize resource management. While CFM programs might constrain households from excessively relying on bioenergy from forests, it is clear that if commons are not carefully managed in some way, forests and other lands are at risk of being over-harvested, consequently creating even greater fuelwood shortages. To effectively reduce energy insecurity, therefore, the complex set of socio-economic, political, and ecological circumstances that give rise to fuelwood shortage must be resolved or otherwise avoided through decreased reliance upon the commons and the energy sources contained therein..

Figure 1: Hypothesized Reference Mode of Gap between Adopted and Implemented Biogas Units in Households (Shaded Region)

As part of their overall strategy to alleviate these pressures on local sources of fuelwood, FES began a biogas unit intervention in 2000. Between 2000 and 2005, they funded the construction of 80 units in the study area. In 2006, additional funding from the Non-

Conventional Energy Department of Andhra Pradesh helped construct 425 more biogas units, bringing the total to 505 units. There is a gap, however, between the biogas units that have been distributed and adopted by households, and their actual implementation or sustained use as the primary source of energy in the household as shown in Figure 1. Specifically, it appears that while households readily adopted the biogas, most used these as supplemental sources of cooking and continued with traditional fuelwoods. Hence, implementation of biogas units as a replacement for traditional fuelwood did not happen.

To achieve household energy security, it will be important to increase, substantially, both the adoption of new sources of energy coupled with the requisite combustion technologies *and* their implementation as intended. Adoption without implementation will not yield the intended benefits of biogas unit dissemination—improved indoor air quality, lower demand for fuelwood from forests for household cooking, and reductions in contributions to outdoor air pollutants, which contribute to the brown cloud hovering over much of Asia at present. While increasing the adoption rate is an important issue which must be addressed, this paper focuses upon the implementation gap as it relates to the realization of energy security on the household level.

The 'energy ladder' theory of energy transition posits that as household income increases, preference for more modern sources of energy develops, leading households to adopt newer fuels and discard traditional, or older forms of fuel (Leach, 1988; Leach, 1992). This theory orders fuels from traditional to more modern. From least to most modern, the fuels are crop residues and animal wastes; fuelwood; charcoal; kerosene; bottled gas/LPG; and electricity (Leach, 1992). The energy ladder theory has been applied to energy transition in both urban and rural areas, although urban households are thought to climb much more quickly due to their increased accessibility to more modern fuels, higher incomes, and greater access to information regarding modern energy sources (Leach, 1992).

Although the energy ladder theory has held significant sway in the development and energy research communities, there are alternate conceptualizations of household energy transition. One argument holds that households' energy *demand* rises with income, but that energy preference is essentially unaffected by increasing income (Foley, 1995). Another argument is that households do not move up the energy ladder replacing older fuels with more modern ones, but instead as household income increases and new sources of energy are adopted, the use of older ones is maintained to a significant degree in order to meet the increasing demand that follows increased income (Hiemstra-van der Horst & Hovorka, 2008). In this way, the "climbing the rungs" dimension of the energy ladder metaphor is viewed as inappropriate, as households do not move from one energy source to the next, leaving the former behind. This argument is further bolstered by the fact that households do not always see fuelwood as an inferior fuel due to its advantages in particular household uses (e.g., boiling water or preparing particular food dishes), so it may be chosen even when income is sufficient and there is access to more modern fuels (Hiemstra-van der Horst & Hovorka, 2008).

All of the households in our study are rural, and there was almost universal use of bioenergy — fuel from fuelwood and agricultural residue. Approximately 21% of households from our study area used a biogas unit for cooking. Among these households, modern fuels were consistently used in conjunction with traditional fuels in order to meet households' overall energy demand. There were myriad factors affecting whether households adopted and used a modern energy source, but household socio-economic status clearly played a central role. Biogas units require 30 kg of cow dung every day in order to operate at full capacity (Community Group Discussion on Biogas (July 29, 2009), Velupalli village, Gudlapalli

Panchayat, Thamballapalli, Chittoor District, Andhra Pradesh, India). FES estimates that a household must own at least two cattle to maintain a biogas unit. Since cattle are expensive to obtain, biogas units remain inaccessible to the poorest households (43% of all households).

Households that adopted multiple cooking technologies were motivated to reduce the time in preparing meals, especially during the agricultural season. June marks the planting season, and farmers are in their fields well into the evening. Before going to their fields, women prepare the morning and mid-day meals. During high agriculture season, some households hire additional help on their farms. Traditionally, the household that owns the land prepares meals for all those working on a field. In such circumstances the ability to prepare food more quickly and in greater quantities with the use of additional cooking technologies provides a significant benefit in terms of saved labor and time. Among biogas adopting households, a common strategy was to use the biogas stove to prepare some food dishes while using the traditional wood stove, or *chulha*, to boil water, since women often reported that the biogas stoves did not boil water fast enough. This strategy was especially helpful for households with greater cooking requirements, those with large families or those who prepared food for agricultural laborers. As our field research indicates, the multiple energy source strategy utilized by most adopting households includes frequent and continued use of traditional wood-burning stoves alongside biogas use. This practice of continued use of traditional stoves partially undermines the benefits of potential reductions in harmful emissions resulting from reduced fuelwood combustion and in environmental benefits resulting from reduced fuelwood extraction.

The literature on diffusion of improved combustion technologies is often separate from that of household energy transition. However, in the case of improved combustion technologies, the decision to adopt is often the result of a complex set of circumstances, including technology design, the new source of energy, and even the household's capacities, needs and preferences. To date, energy conservation interventions attempting to distribute improved combustion technology to the poor have enjoyed uneven success. Programs and policies have been implemented on the assumption that households will adopt new technologies simply because of an expected improvement in health, economic, and environmental outcomes associated with a shift to newer fuels or technologies that are more efficient. This view, however, ignores factors acting alone or in combination to influence household behavior to take up new technologies, and sustainably use such technologies. For instance, when fuelwood and/or crop residue are readily available, the incentives to shift to newer forms of energy or adopt more efficient combustion technologies are feeble in comparison to other possible uses of households' scarce resources (Feder et al, 1985; Heltberg et al, 2000).As previously stated, the rural poor may deploy multiple strategies to cushion households from energy insecurity, stacking newer technologies on top of tried and true older combustion technologies, thereby undermining some of the gains from the take up of new combustion methods or alternate sources of energy.

Theories of innovation diffusion host divergent views around the actual mechanism of diffusion. To drastically over-simplify, two major trends are present: (1) potential adopters, be they individuals or households, act rationally to decide whether or not taking-on a new innovation maximizes utility (Rogers, 1995); (2) potential adopters are influenced through social networks and cultural learning to adopt new innovations (Axelrod, 1997; Haggith et al, 2003). This literature speaks not just to the dissemination and adoption of improved combustion technologies, but to all innovations. While the various details of general theories may not be best suited for application to the case of combustion technology innovations as they are distributed in rural areas of developing nations, from our field research and from the development literature, we deduce two broad categories of important factors at work in systems of variables proximate to the household decision-making process, both of which link-up roughly with the trends in general innovation theory described above.

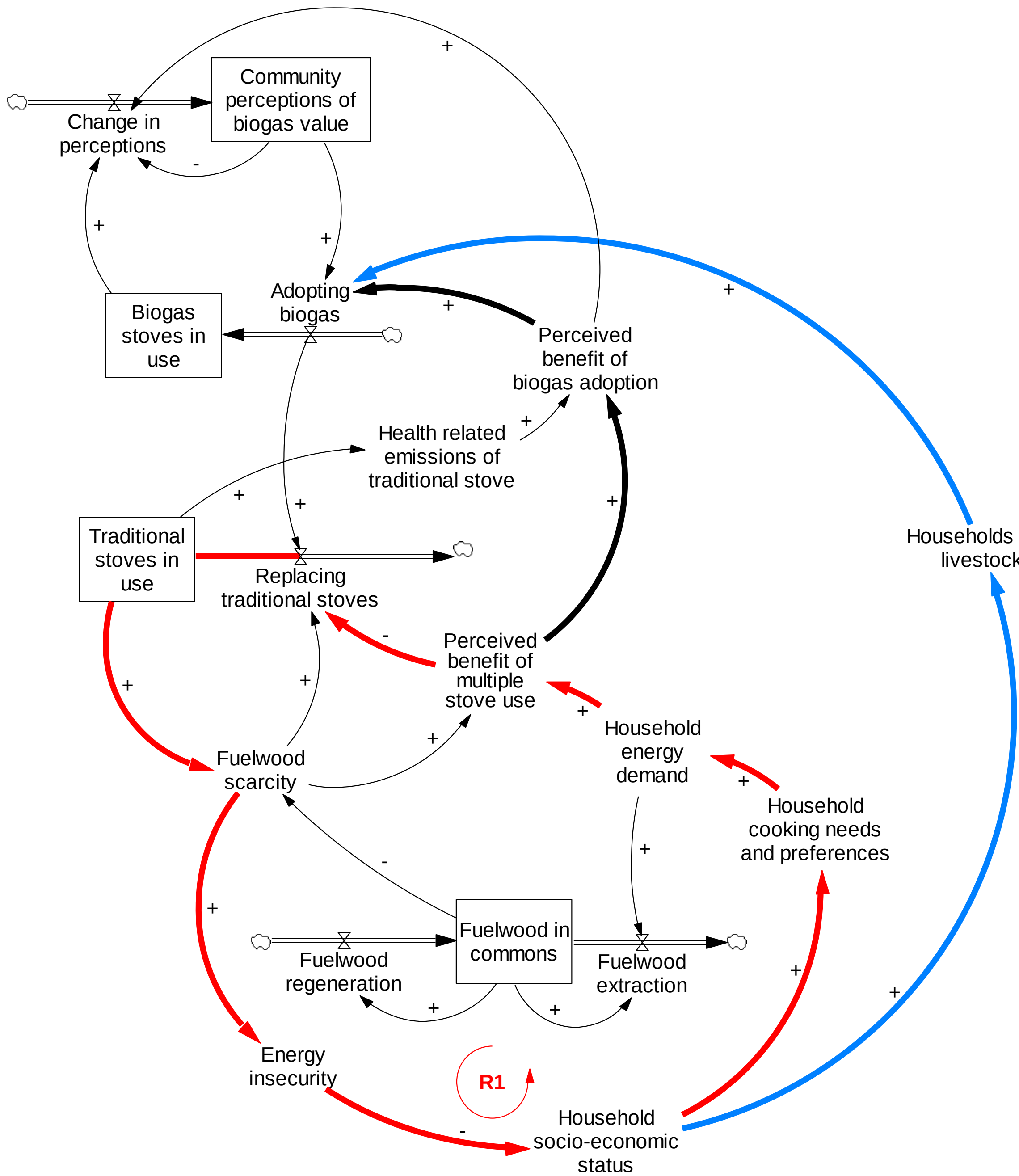
The first regards household benefit-cost perceptions. "Household benefit-cost perceptions" refers to a process wherein each household weighs the benefits and costs of taking on an improved combustion technology, including initial costs and benefits, and those that will accrue over time. FES's efforts around disseminating biogas plants entailed lengthy consultation sessions with households where the technology was introduced and explained to household members by FES out-reach workers. FES described considerable difficulties in persuading households to adopt biogas units. Most efforts were unsuccessful. In successful cases, there were repeated consultations in which FES out-reach workers answered households' questions regarding the technology, so that a household could determine if a biogas unit would be a good fit for their overall energy strategy. Consistent with our field experience, many authors have identified that the complex set of social, cultural, economic, technical, and ecological factors affecting households' perceptions of the benefits and costs of adopting new combustion technologies are key in the adoption decision (Agarwal, 1983; Amacher, Hyde, & Joshee, 1992; Barnes, et al, 1994; Feder, Just, & Zilberman, 1985; Muneer & Mohamed, 2003; Smith, et al, 2007).

Second, the degree to which households have access to information about improved combustion technologies determines whether or not they will adopt. Households engaged in daily activities outside the household are more likely to use improved combustion technologies (Macht, Axinn, & Ghimere, 2007). In theory, household members will hear of new technology at markets, schools, and other non-family organizations and institutions, making them more likely to adopt. This is also consistent with theory suggesting that cultural learning is in part responsible for adoption (Axelrod, 1997; Haggith et al, 2003). Macht, Axxin, and Ghimere find evidence that community context to an extent determines households' decisions around fuel and combustion technology choice (2007). All of the factors herein discussed, regarding both energy transition and technology diffusion, must be considered in an intervention if the worst effects of continued biomass combustion are to be averted.

Model

Household adoption of biogas plants involves significant dynamic complexity. We propose the following model shown in Figure 2 as a potential explanation for the implementation gap shown in Figure 1. Based on our surveys, observations, interviews, and literature review, we believe that this decision is driven by households' weighing of the utility of adding a biogas unit to their current energy strategy – the approach the household takes to meeting its specific energy demand by employing various combustion technologies and the related sources of fuel. As previously stated, all households use traditional bioenergy from wood and crop waste in indoor and outdoor stoves, or *chulhas*. The addition of a biogas unit might provide benefits if household energy demand is high due to increasing energy production functions, large household size, or provision of meals for agricultural laborers. A key driver of adoption is that some benefits are perceived in the ability to use multiple stoves simultaneously in order to prepare the household's normal amount of food more efficiently, re-allocating extra time to other tasks.

Figure 2: Household Biogas Adoption and Traditional Technology Replacement



"Perceived benefit of biogas adoption" is directly impacted by "Household cooking needs and preferences." This variable represents households' various concerns around the food preparation process. Households' cooking needs and preferences influence their willingness to adopt new devices based on ease of use, the ability of a device to prepare particular dishes the household prefers, whether or not a device can be left to operate while household members perform other tasks, whether it is messy to use, and other such factors. If a device's performance does not meet households' cooking needs and preferences in these ways, they are less likely to adopt it.

"Health-related emissions of traditional stove" also impacts the "Perceived benefit of biogas adoption" directly. As discussed in the introduction section of this paper, traditional wood-burning stove emissions are the cause of considerable health issues among stove users. Further, the smoke emitted during the cooking process is very uncomfortable for users and provides some motivation for adopting cooking devices that emit less. In terms of the biogas intervention's impact upon social welfare, reducing serious negative health outcomes associated with stove emissions may or may not be a primary objective. While health issues are burdensome they are not usually a priority for household decision-makers or stove users. In our field experience, stove efficiency and fuelwood scarcity seem more relevant as drivers of biogas adoption.

Households engage in implementation decision-making to determine the extent to which the biogas unit will be used in the overall household energy strategy. It may not be, and is almost always not, beneficial to households to use the biogas unit as the sole source of cooking energy. Around this notion, a central driver of the adoption decision, "Perceived benefit of multiple-stove use", is also one of few drivers of the replacement rate. As the perceived benefits of a multiple-stove strategy increases in the system, a simultaneous reduction in "Replacing traditional stoves" occurs. In short, the dynamics that increase biogas adoption are also associated with decreases in traditional stove replacement, so long as it is advantageous to adopt a multiple stove strategy. In our sample, no households with biogas stoves had stopped using their traditional stoves, and biogas households still use traditional sources of energy to a significant degree.

"Adopting biogas" is impacted by several factors. Perhaps the most critical of these is the percentage of "Households with livestock," since livestock ownership is a pre-requisite for biogas unit operation. Biogas units require 30 kg of cow dung daily to produce fuel on a regular basis. As we note above, 43% of households did not have sufficient livestock to maintain a biogas unit, and so were immediately excluded from the intervention.

"Perceived benefit of biogas adoption" is directly impacted by "Perceived benefit of multiple-stove use," which we are hypothesizing is primarily driven by the reinforcing loop R1 (red path in Figure 2). In R1, "Traditional stoves in use" contributes to "Fuelwood scarcity", which increases "Energy insecurity" keeping "Household socio-economic status" low. Lower "Household social and economic status" reduces "Household cooking needs," which then reduces "Household energy demand," a primary driver of "Perceived benefit of multiple-stove use." This dynamic ultimately thwarts "Replacing traditional stoves" and "Adopting biogas."

This central dynamic was brought to life during our field experience. Poorer households faced food insecurity and, because of it, were less concerned about the effects of energy insecurity as energy demand was relatively low without enough food to cook. Over time energy insecurity, perversely and counter-intuitively, actually reduces the need for alternate cooking technologies and energy sources. Through interviews with villagers, we learned that households in poverty, a poverty bolstered by energy insecurity tied to use of traditional stoves and the resulting fuelwood scarcity, would eventually feel much less need to add improved cooking technology and alternative energy sources because of the reduced energy demand connected to reduced cooking needs.

Also, we interviewed households who were facing rising fuelwood scarcity but lacked the socio-economic capacity to adopt biogas plants. Households that have sufficient livestock or capital to obtain livestock likely will adopt biogas plants, assuming they determine that biogas is consistent with their household needs (blue path in Figure 2). This subset of the population allows for the slowing of the deleterious impacts. But those households residing beyond this subset without adequate SES (43% of households in our sample), will continue to meet their rising energy demand using fuelwood from common stocks.

Discussion

Our primary aim has been to impact FES's work around energy conservation in the Papagni River Basin, contributing to an understanding of the dynamics of the energy-environment-poverty nexus as it relates to their biogas intervention. We also believe that similar organizations working in India and other developing nations can also benefit from our work here. It is also our hope that policy makers focusing on public health and energy conservation in rural development will use this study to better understand the challenges they face in reducing the negative ecological, economic, and human health outcomes of continued biomass combustion.

A few limitations of our study are important to consider before giving a more thorough discussion of its implications. First, the model's generalizability is limited by the inductive nature of our undertaking. We elucidate a problem of intervening on challenges at the intersection of human development and ecological conservation as it persists in a specific socio-geographic context. While it is likely that some of our variables and the feedback structures they establish exist in other contexts as well, we can only knowledgeably outline the structure of the system in our study area. Therefore, our conclusions should be interpreted with sensitivity toward differences in the socio-geographic context of our study area and that to which this analysis may be relevant. Similarly, the precision that would come with quantitative modeling is not realized in our model; it is not certain to what extent the dynamics between variables are influencing one another. Lastly, it is important to recognize that this model remains in the preliminary stages of development and will continue to grow, reflecting further evidence made available through return visits to the field, as well as developments in the broader energy transition and technology diffusion literature.

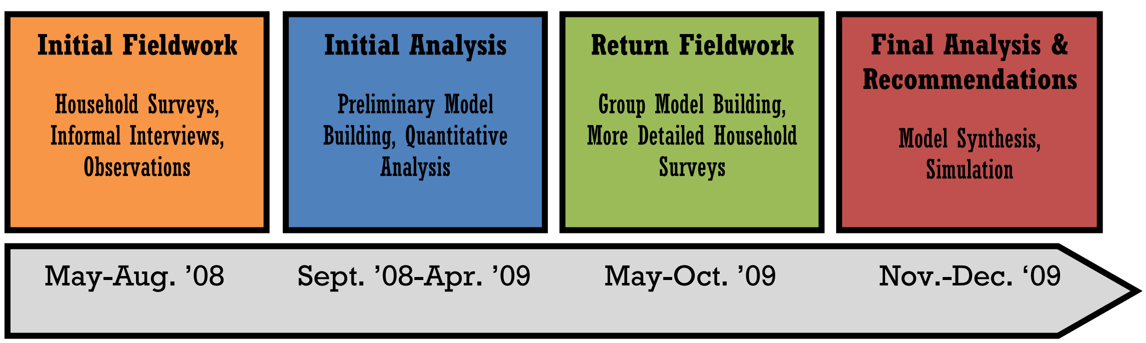
Despite these limitations, this model is still useful. The study of dynamic complexity is crucial for understanding coupled human and natural systems, the energy, environment, poverty nexus, of which sustainable household energy use in the context of rural development is a central example (Liu et al, 2007). Over the last few years, many authors have argued for the need of innovation in research methodologies in order to capture the non-linearities, surprise effects, feedbacks, and interactions between social and ecological systems (Agrawal, 2007; Ostrom, 2007). This call is in response to a broad recognition that a simplistic understanding of dynamic complexity has led to significant failures in natural resource management and human development policy (Ostrom, 2007; Janssen, Anderies, & Ostrom, 2007). By modeling the problem addressed in this case with a dynamic model and a view to understanding the underlying feedback structures responsible for the behavior of the system in which the problem lies, we take a step closer to providing useful analyses and recommendations to FES and other organizations working at the intersections of human development and natural resource management.

This model can serve as an important tool for problem conceptualization and discussion within FES as they further implement their biogas intervention. An important step in improving this intervention consists in conceptualizing the problem in a way that accounts for all the major drivers of biogas adoption and implementation at the household level. In this case, our model reveals two central system behaviors that are highly salient. First, the continued use of a multiple stove strategy over and against technology replacement has significant repercussions upon the realization of intervention goals, namely reductions in the aforementioned negative outcomes around human and ecological health. Therefore, it is crucial to understand why households are using this strategy. We find that the very same drivers of biogas adoption constrain the potential for traditional energy source replacement. This indicates that the underlying forces behind a household's perception of benefits in using multiple devices, notably energy demand and fuelwood scarcity, will have to be sufficiently addressed by biogas interventions or other related interventions on energy efficiency and emissions reduction if the desired outcomes are to be realized.

Second, as our model demonstrates, feedback processes actually keep households in poverty through increased energy insecurity, ultimately preventing significant levels of biogas adoption in a timely manner. Households that are not able to adopt more energy efficient combustion technologies due to social and economic constraints when facing fuelwood scarcity may fall into energy insecurity, which in turn maintains the levels of poverty, frustrating possibilities for further adoption. Again, any successful biogas intervention will have to address the social and economic factors preventing initial adoption of biogas technologies to prevent the worsening effects of energy insecurity on biogas adoption, including continued fuelwood scarcity.

Beyond FES' internal usage, these models will form the preliminary models for a group model building (GMB) process with rural villagers in our study area (see Figure 3). The study team is presently preparing to return to the field to continue our work to better understand the household and community level problems of energy conservation and technology adoption and diffusion.

Figure 3: Research Plan



In this paper, we have analyzed the underlying dynamics determining outcomes of biogas intervention in southern India. We suspect that similar dynamics are at work in similar energy-environment-poverty interventions in other contexts, so our work here is useful in that regard. Organizational learning in the midst of an intervention is highly important in order to correct for problems preventing the attainment of intervention aims. This analysis provides an opportunity for FES to consider the state of the problem as it stands now and alter the course of intervention to bring in households with significant socio-economic constraints. As we take this work into the future, further recommendations will be made to facilitate updates, progress in learning, and respond to changes in the intervention process.

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