Dynamics of sustained use and abandonment of clean cooking systems: lessons from rural India

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Abstract

Clean cooking technologies—ranging from efficient cookstoves to clean fuels—are widely deployed to reduce household air pollution and alleviate adverse health and climate consequences. Although much progress has been made on the technical aspects, sustained and proper use of clean cooking technologies by populations with the most need has been problematic. Only by understanding how clean cooking as an intervention is embedded within complex community processes can we ensure its sustained implementation. Using a community-based systems dynamics approach, we engaged two rural communities in co-creating a dynamic model to explain the processes influencing the uptake and transition to sustained use of biogas (an anaerobic methane digester), a clean fuel and cooking technology. The two communities provided contrasting cases: one abandoned biogas while the other continues to use it. We present a systems dynamics simulation model, associated analyses, and experiments to understand what factors drive transition and sustained use. A central insight of the model is community processes influencing the capacity to solve technical issues. Model analysis shows that families begin to abandon the technology when it takes longer to solve problems. The momentum in the community then shifts from a determination to address issues with the cooking technology toward caution in further adhering to it. We also conducted experiments using the simulation model to understand the impact of interventions aimed at renewing the use of biogas. A combination of theoretical interventions, including repair of non-functioning biogas units and provision of embedded technical support in communities, resulted in a scenario where the community can continue using the technology even after support is retracted. Our study also demonstrates the utility of a systems approach for engaging local stakeholders in delineating complex community processes to derive significant insights into the dynamic feedback mechanisms involved in the sustained use of biogas by the poor.

Introduction

Substantial empirical evidence points to the harmful environmental and health impacts of ambient and household air pollution (HAP) [1–9]. Reducing HAP, which impacts almost 41% of the global (mostly poor) population [10], improves both health and environmental outcomes. The UN has therefore committed to providing affordable, reliable and sustainable modern energy for all as one of its sustainable development goals (SDG Goal 7) [11]. Two parallel efforts are underway to address this challenge of HAP: (1) on the technology side there is a vigorous effort to develop cleaner and efficient cooking technologies, and renewable energy technologies to reduce exposure to harmful emissions from both HAP and ambient air pollution; (2) social, behavioral and public health researchers have focused their efforts on understanding a range of determinants including technical aspects, which could drive the adoption and sustained use of these technologies in energy-poor communities. Technological efforts to develop better cooking alternatives and clean energy systems have received considerable attention and support [5, 12]. Commensurate emphasis
has not been given to understanding social, ecological and behavioral factors driving the adoption and sustained use of clean cooking practices in energy-poor communities [5, 13, 14].

Improved cookstoves (ICSs) have received considerable focus as technologies to address HAP in energy-poor communities [15–18]. Most of these ICSs are low cost and targeted to poor communities [5, 12]. However, adoption and use of ICSs are saddled with their own set of challenges. HAP exposure-response curves are non-linear in nature [1, 2, 19]. Health benefits can be derived only at very low levels of exposure [2, 4]. For substantial health benefits from clean cooking, the World Health Organization (WHO) recommends reduction in PM$_{2.5}$ exposure levels to 35 µg m$^{-3}$ [20, 21]. Most ICSs exhibit poor performance against the WHO’s recommended indoor air quality guidelines (IAQGs) in the actual household scenario. Emissions performance of multiple models of ICSs against the ISO’s International Workshop Agreement’s (IWA) tiers have shown that none of these stoves could be placed in tier 4 in terms of emissions performance [22]; they are mostly placed in tier 1 and tier 2 [22]. Health-related benefits are thus compromised despite switching to ICSs. Further, this shift does not insulate communities from relying on biomass as a fuel. Anthropogenic degradation of forests and the drudgery of collecting biomass continues [23]. Adoption of ICSs also does not ensure a complete abandonment of traditional biomass stoves.

Use of multiple stoves (also known as stacking) combining traditional cooking stoves and ICSs is routine in such poor communities [15, 24–26]. There has been a recent emphasis to develop strategies to push IWA’s tier 4 cooking systems in energy-poor communities. Liquefied petroleum gas (LPG), induction stoves and biogas digesters are tier 4 clean cooking technologies with emissions below the WHO’s required IAQGs [22]. LPG and induction stoves are mired with multiple issues of affordability and accessibility, especially in poor communities of rural India [27]. Biogas digesters (biogas) could provide a viable solution for low-income rural communities, where affordability and accessibility to LPG or induction stoves is still a challenge [20]. However, adoption and sustainment (with no stacking) of biogas in these rural communities remain significant impediments [28–30].

Tricket and colleagues [31] argue that sustaining evidence-based practices to achieve intended outcomes is one of the most important aspects of community level interventions. Such interventions are often embedded within complex community processes, further complicating the goal of sustainability. The dynamic interaction of the intervention with community processes underscores the need to work collaboratively with communities and recognize the importance of their knowledge and involvement in intervention processes. A collaborative approach also helps to close the gap between knowledge development and knowledge use [17–19]. The issue of adoption and sustained use of biogas is complex. This complexity arises not only from a high number of factors [32] but how they interact with each other. Social, economic, environmental and technological factors interact in nonlinear relationships to form feedback processes with time delays. The cause of the problem behavior, in this case a persistent trend of low uptake or high rate of abandonment of clean cooking technologies such as biogas over time, cannot be attributed to a few independent factors but rather to how the processes are structured in a set of interacting feedback mechanisms. Methods with a unidirectional approach and inability to incorporate contextual processes are less suitable for developing insights into problems embedded in complex community systems [33, 34]. A systems perspective is necessary to understand the dynamic interplay of social, ecological and technological factors driving the adoption and sustained use of clean cooking systems such as biogas.

There is a paucity of literature deploying systems thinking in exploring the determinants of adoption and sustained use of clean cooking technologies in energy-poor communities [14, 20, 35]. More specifically, these determinants in the context of biogas for these communities have been barely studied, and merit closer inquiry [20]. Using biogas as a representative clean cooking technology in rural poor communities of India, the current study and its results bridge this gap in our understanding of the drivers of the uptake and sustained use of clean fuels for cooking. Without a robust assessment of the determinants impacting the adoption and sustained use of biogas, the challenge for energy-poor communities will persist despite biogas being a viable technological solution for HAP. The study also provides key behavioral insights, which could be tailored and adapted to promote adoption and sustained use of other clean cooking systems in many energy-poor communities.

**Methods**

To understand the complex community processes shaping the sustained use of biogas, our study uses the community based system dynamics (CBSD) modeling approach [36, 37]. System dynamics is a computational modeling approach which focuses on understanding the relationship between the feedback structure of the underlying system and the resulting system behavior [38]. The relationships in the model are defined as a system of differential equations and solved computationally. We use Vensim DSS software (Ventana Systems, UK) to develop our model and its simulation. System dynamics has been used in studies of diffusion of innovation [39] and community level interventions [40].

The primary goal of this pilot study was to explore the applicability of the CBSD approach in understanding the dynamics of sustained use of clean cooking
technology. Although this letter will describe the approach, it is important to note that details including a description of the study design and steps involved in implementing CBSD have been described elsewhere [37]. The data collected in this study are at the aggregate level and do not include any individually identifiable information. Therefore, the Human Research Protection Office at Washington University in St. Louis has determined that this study does not involve activities that are subject to Institutional Review Board oversight.

Data sources

The model and simulation results presented in this paper are based on group model building sessions with two communities, one of which was able to sustain the use of biogas and another that abandoned the technology. The two communities are located in Bhilwara district in rural Rajasthan, India. The local partnering agency implemented a biogas project with both communities at the same time, creating an ideal situation for a comparative study. These communities are also adjacent to each other and therefore share similar geophysical conditions. The study site is a drought-prone region with an average yearly rainfall of 690 mm. Most of the households in both villages have small landholdings and depend on rain-fed agriculture as their primary livelihood, which is supplemented by wage labor. Households are dependent on nearby forest for fuelwood, non-timber forest products, timber for construction and fodder for livestock. Table 1 highlights some of the demographic and socioeconomic characteristics of the two villages.

Data for the reference mode and the model structure were collected during the CBSD modeling sessions. Reference mode refers to a graph depicting change in a variable measuring a behavior of interest over time. The model structure refers to the feedback mechanisms causing behavior change over time. A day long model building session was conducted with groups from each community. Each session had a minimum of ten participants from the community. The number of participants reflects the best practice in group-based participatory modeling [36]. The participants were not selected in a representative manner. The field staff representing the local agency partner visited the villages prior to the CBSD session and asked for female volunteers who would be interested in taking part in the study. While the model was built with the women who volunteered, the reference mode and the model were subsequently presented to non-participating members of each community, for member checking [41], to ensure that the narrative was accurately represented in the feedback mechanisms. We adapted the ‘timeline’ exercise used in participatory rural appraisal [42] to develop the reference mode. We asked the participants to re-construct a timeline based on major events in the community’s history. Thereafter, the facilitator asked participants to identify the number of families using biogas at the time of each event. For every time point, the facilitator checked whether the data from the implementing agency corroborated the participants’ recall. At times when there was a discrepancy, the facilitator would ask questions regarding the particular households that installed biogas that year. This allowed us to develop trends of biogas over time in each community while orienting the group to conversations around biogas installation and use. Instead of presenting the agency-based data to the volunteers we were able to develop the total number of biogas units in a community through participatory methods.

Building the system dynamics model

During the CBSD process, participants shared a narrative based on their lived experiences with the technology. In real time, the research team developed a model that represented the participants’ narrative as a set of feedback mechanisms. These mechanisms delineate a set of interrelated hypotheses explaining the sustained use of biogas over time. These interacting mechanisms, non-linear in nature with time delays, make it difficult to cognitively infer the behavior of the system over time [43]. Therefore, mathematically defining the feedback mechanisms to simulate the model is crucial to determine whether the set of mechanisms identified in the model can reproduce the reference modes of interest in this study.

The core of the model represents the movement of families through various stages of their experience with

| Number of households | Sustained | Abandoned |
|----------------------|-----------|-----------|
| Total population    | 120       | 706       |
| Adults               | 53        | 415       |
| Male                 | 42        | 217       |
| Female               | 26        | 198       |
| Children             | 43        | 291       |
| Male                 | 23        | 171       |
| Female               | 20        | 120       |
| Caste distribution   |           |           |
| Household (Households) |         |           |
| Scheduled caste (SC) | 0         | 18        |
| Scheduled tribe (ST) | 21        | 143       |
| Other backward caste | 0         | 28        |
| (OBC)                |           |           |
| Type of house        |           |           |
| Concrete             | 15        | 34        |
| Adobe                | 18        | 155       |
| Semi-concrete        | 0         | 0         |
| Occupation           |           |           |
| Agriculture          | 15        | 136       |
| Agricultural labor   | 2         | 4         |
| Other labor          | 13        | 44        |
| Service              | 0         | 4         |
| Self employed        | 1         | 1         |
| (non-agricultural)   |           |           |
| Other                | 0         | 0         |
| Households below poverty line | 26 | 123   |

Table 1. Demographic and socioeconomic attributes of the two villages.
biogas (figure 1). Families at each stage are represented in stocks, which are variables that can accumulate over time, and their values depend on the rate of inflows and outflows. If the inflows and outflows are equal (i.e. netflow = 0) the level of the stock will be in equilibrium.

The first stock is families using traditional cookstoves, which represents the initial number of families in a community using traditional cooking methods. They transition into the stock of families using both traditional and biogas as the flow increases, represented in the installation rate of biogas. This stage is referred to as ‘stacking’ where, instead of replacing the traditional stove, families use it simultaneously with a cleaner cooking stove. In the stove stacking stage, families are experimenting with and learning about the new technology with the security and backup of a tried and tested traditional stove. From this stage, they either transition to join other families predominantly using biogas or abandon the technology and transition to being one of the families with non-functional biogas. Table 2 provides an example of how the variable installation rate of biogas was formulated.

The term ‘predominantly’ highlights the reality of rural households where traditional cookstoves are never completely abandoned but are used on occasion and in emergencies. Households in this state, however, use biogas for their daily cooking. Similarly, the term ‘non-functional’ highlights that the primary reason for abandonment is due to malfunction of the new technology. The participants identified various reasons for a malfunctioning stove, from broken valves to water seepage in the digester, and lack of methane production due to clogged pipes. Participants described a period between encountering a malfunction and deeming a biogas plant non-functional. The length of this period was based on their motivation to use the biogas unit and knowledge of the technology. If the time to solve issues was longer than they were willing to wait, they would give up and consider that biogas plant non-functional. At this stage, the technology was not beyond repair, and could still be made functional. However, once the participants transitioned out of this stage, repairing the technology was not an option. It should also be noted that families who predominantly shifted to using biogas might also abandon the technology as it became non-functional over time.

Each of the transitions (i.e. flows) is driven by a structure of feedback processes. The transition, installation rate of biogas, is driven by two feedback processes. First, through the process of advocacy and promotion, government and non-government organizations convince families and communities to install biogas. In our study area, the Foundation for Ecological Security (FES) worked with community members to spread awareness of biogas. They even arranged for families to visit a nearby village to demonstrate how others were successfully using it. Some families installed the new technology following such promotional campaigns. Second, as families install the new technology, those without biogas are motivated to install it through word of mouth. This is a reinforcing process—as the total number of families using biogas increases the rate of installation also increases. Social networks and contagion are significant driving factors, initially.
Table 2. Description of variables, units, and formulation used in defining the installation rate of biogas.

| Variable                                      | Definition                                                                 | Units          |
|-----------------------------------------------|----------------------------------------------------------------------------|----------------|
| Installation rate of biogas                   | Installation through advocacy and promotion + Installation through word of mouth | Households/month |
| Installation through advocacy and promotion   | Families using traditional stoves + Effectiveness of advocacy and promotion | Households/month |
| Effectiveness of advocacy and promotion       | Fraction of households currently using traditional stove that would install biogas based on advocacy and promotion by implementing agency | Households/household/month (Households installed/households reached/month) |
| Installation through word of mouth            | Total families using biogas * Social interaction among community members * Fraction of interaction resulting in installations | Households/month |
| Social interaction among community members    | Number of contacts an average household makes with other households in the community | Contact/month |
| Fraction of interaction resulting in installations | The probability of installing a biogas based on contacts made with households who have already adopted | 1/contact |

As the number of families using biogas rises, it contributes to the knowledge needed to properly maintain the technology and troubleshoot problems in a timely manner. External recognition of a community’s efforts to shift to biogas is also an important mechanism. External recognition can come from local and national government and non-government organizations. Our modeling indicates that this is an important driver in motivating community members to resolve issues and continue using new cooking technologies. Both knowledge of the new technology and external recognition drive the processes to reduce the number of issues and the time it takes to successfully resolve them (figure 2).

Model testing
Testing a system dynamics model involves reproducing the behavior of the real system and ensuring the logical consistency of the feedback mechanisms. The goal of testing is to increase confidence in the model and uncover errors [38, 44]. In figure 3, we show both the sustained use and abandonment behaviors over time based on data and then compare them to our simulated data. The goal for the model is to elicit an underlying structure of feedback mechanisms that produce qualitatively similar behaviors to the real world. In other words, the goal is to reproduce general scenarios showing either initial uptake and sustained use or initial uptake and abandonment. Therefore, statistical comparisons of the data and the simulations are not performed. The variation in behavior (i.e. sustained use versus abandonment) is a result of changing parameter values that represent two distinctions in the communities. First, firewood was more accessible in the community that abandoned the technology, which is represented in the model as a driver lowering motivation to solve issues and continue using biogas. Second, this community also faced more challenges in the introduction phase. For instance, one of the families abandoned their new biogas unit because water had seeped into the digester.

This is a costly and time-consuming issue to solve. To reproduce the abandonment behavior, our model is calibrated by varying the values for initial motivation to use biogas and the initial time it takes to resolve issues.

Reproducing the behavior from the system is the first step in gaining confidence in the model. Our model reproduces the sustained use behavior well. It underestimates the maximum number of families using biogas in the village where it was abandoned but matches the overall pattern of initial uptake followed by abandonment. Reproduction of data is considered a weak test in examining the logical consistency of the model [38]. Therefore, we performed a dimensional consistency test and sensitivity analysis to build confidence.

Each variable in the model has a defined unit. As an example, installation through advocacy and promotion is represented as households/month. This variable is a product of families using traditional stoves and installation through advocacy and promotion. When the units of these two variables, households and 1/month, are multiplied the resulting unit is households/month. Units on both sides of the equation are consistent. A built-in function tests the dimensional consistency of all the equations and provides a list of errors. The final model passed the dimensional consistency test.

There are numerous parameters with uncertain values in the model. An important test is to understand the sensitivity of model behavior to the uncertainty in the parameters. To conduct the sensitivity analysis, we first calibrated the model parameters to produce the ‘sustained use’ scenario and varied each parameter (+/− 50%) individually and graphed the resulting behaviors. As shown in figure 4, 100% of the simulation runs based on the sensitivity analysis result in a sustained use pattern of behavior. In other words, the model behavior is sensitive to variation in the parameters. The overall model behavior (i.e. sustained use), however, is robust.
Testing intervention scenarios

The value of developing a mathematical model is the ability to test interventions and examine counterfactual scenarios. Such experimentation at a community level can be very expensive or is often not feasible. A simulation environment provides a platform for quick experimentation and learning that can pave the way for future studies. Three interventions were chosen for testing based on discussions with community members and the local implementing agency (table 3). For example, community members mentioned that they would use the technology if it was repaired. Therefore, the repair scenario was tested to understand what would happen if all the non-functional technologies were repaired. The cost or time taken to repair all the non-functional biogas units was not taken into account. The goal was to test what would happen in the best case scenario where all repairs were completed instantaneously. If the outcome was not positive in this scenario, constraints such as cost and time would further diminish the outcome. Similarly, the local agency partner mentioned how a community becomes motivated by visits from governmental...
Table 3. Three interventions tested in the model to alter system behavior from abandonment to sustained use.

| Interventions                               | Period       | Nature of the intervention                                                                 |
|---------------------------------------------|--------------|-------------------------------------------------------------------------------------------|
| Repair non-functional biogas                | 2014–2016    | Moves 100% of the families with non-functional biogas to families using both biogas and traditional stove for the time period |
| Provide external recognition and encouragement| 2014–2019    | Increases external recognition and support of community shift to biogas by 100% for the time period |
| Improve effectiveness of technical support  | 2014–2019    | Reduces the time it takes to solve issues such that problems are solved almost immediately for the time period |

and non-governmental agencies and universities. The ‘external recognition and encouragement’ intervention was tested to understand the impact of visits from outside groups.

The first intervention repairs all the non-functional biogas technologies. The families whose biogas were non-functional and were not repaired, under this scenario, receive a one-time intervention transitioning them to families using both traditional and biogas. In the model, the ‘fractional rate of repairing biogas’ was changed to one between the years 2014 and 2016. The second intervention increases external recognition and encouragement of community and household behavior to shift to biogas. The successful community, in our group model building session, confirmed that recognition from various governmental and non-governmental organizations increased their motivation to keep using biogas. This recognition went up as more families in the community adopted and sustained the use of biogas. The intervention created additional encouragement regardless of the number of families using the technology. In the model, the ‘external recognition and intervention’ variable is changed to one between the years 2014 and 2019. This represents a 100% increase in the natural rate of external recognition.

The time it takes to solve issues also plays a crucial role in the sustained use of the technology. When issues are not resolved in time the new technology becomes non-functional and leads to lowering of perceived benefits. Our intervention reduces the time to solve issues, which is possible, according to the female volunteers, through technical assistance and as knowledge about the intervention becomes embedded in the communities over time. In the model, the ‘average time to solve issues’ is reduced such that issues are solved almost immediately between the year 2014 and 2019.

To determine how the magnitude of interventions affects the sustained use of biogas, we vary the levels of encouragement and technical support of interventions from non-existent to the highest level (100%). The repair interventions and the timing are kept similar to previous scenarios. Simulation results (final year: 2030) are exported to Microsoft Excel and organized as a 2 × 2 table with one intervention as a column and another as a row. Finally, we developed a surface plot to highlight how the number of families using biogas changes with variation in the two interventions, independently and in combination.

Simulation results

As shown in figure 5, repairing all the non-functional biogas technology has an immediate impact as the number of families using it increases. However, the
processes involving delays in solving issues that lead to abandonment have not been altered. As issues arise and families are unable to resolve them in a timely manner, biogas digesters are abandoned. Supplementing the repairs with encouragement has some impact, but is unable to qualitatively change the system behavior over time. Although the motivation to sustain the use of the technology increases, it still takes families a long time to solve issues, resulting in the disuse of biogas. Only with the addition of technical support do we see a shift in shortening the time it takes to resolve issues and eventually in the system behavior from abandonment to sustained use. We define ‘sustained use’ at the community level as the cumulative number of families using biogas which includes those who have come back to it and households that have adopted it for the first time. When the model shows sustained behavior after the interventions, it is again showing a combination of families returning to biogas that had once abandoned the technology and the new families that have adopted it for the first time.

The system behavior of biogas in our simulation is insensitive to changes in the magnitude of external encouragement intervention (figure 6). The plane of the surface plot on the x-axis is nearly flat. The reduction in time to solve issues as a consequence of improved technical support has a nearly linear relationship with the outcome but the effect of technical support plateaus such that a further increase in technical support would not have any impact on number of families using biogas.

Discussion and conclusion

Our study is one of the first to develop a dynamic model of clean cooking adoption, implementation and maintenance. We also show how a novel approach like community based system dynamics can derive insights from key stakeholders—women in rural areas. Our model highlights the various feedback mechanisms salient in understanding the way women eventually have to negotiate the many complexities of the intervention deployed to improve their health and well-being in the context of their own lives. As a result, even minor differences in the intervention can result in sustained use or abandonment of a technology. One of the advantages of using system dynamics modeling is highlighting how similar feedback structures, such as those in these communities, can result in drastically different behaviors due to an accumulation of small variations over time.

The model building process and analysis show that introducing biogas to rural communities is a complex process that spans the social, ecological and technological domains [20]. Understanding the structure of feedback mechanisms across these domains is critical to enabling rural communities to adopt and sustainably use these technologies. Clean cooking interventions fail when understood in isolation of household and community dynamics. Engaging women and key community stakeholders to develop the initial model improves its representativeness and creates an environment for sharing insights between researchers, local implementing state and non-state agencies, and communities. The study tested three concurrent interventions and found that technical support and assistance can play a crucial role in shifting households from traditional stove use to adopting and sustainably using biogas digesters. The other two interventions, including fixing disused biogas and motivating households to use it without proper technical support, may not yield positive results. These findings reiterate previous research on factors impacting installation and use of biogas in rural low-income communities. Bond and Templeton [28] and
Lewis et al [20] have noted that biogas offers significant promise for addressing HAP in rural poor communities. However, it faces operational and technical challenges in routine practices [20, 28]. Low awareness to fix operational issues on a timely basis and lack of technical training (especially for women) exacerbates the scenario [28, 45].

Our findings show that as biogas use overall in a community changes, it also drives the level of technical knowledge embedded in that community. As this knowledge is embedded, it helps resolve issues. So, in part the level of necessary technical support in a community is a function of how much technical knowledge has accumulated due to the number of biogas users. How additional technical support is provided through external funding beyond the already accumulated knowledge of biogas use in communities is therefore an important question to examine. We do this through simulating the introduction of technical support. Our simulation demonstrates that higher levels of indigenized technical knowledge is more sustainable in combination with small amounts of technical support from the outside as needed. Our results highlight that providing timely repairs and technical knowledge (especially for women) can sustain biogas use in these communities, although funding mechanisms and willingness to pay among users for such external technical support need further exploration, and this is beyond the scope of our model. Anecdotally we observed that social networks of women and opinion shapers in these communities are instrumental in providing motivation and encouragement to users. Future studies should expand the scope of the research to incorporate the role of gender-based social networks in clean energy transitions.

Our findings not only validate the existing line of insights from Mirza et al [45], Lewis et al [20] and Bond and Templeton [28] but also extend these arguments by emphasizing that merely encouraging communities to use clean cooking is not sufficient. Time to experiment with, understand and experience the advantages of clean cooking are also important. Increasing technical knowhow and embedding it within communities, particularly in women, ensures that even as problems arise on the technical front, they are resolved in a timely manner. Resolving issues in the use of new technologies not only increases the technical knowhow but also the confidence to implement and maintain new clean cooking methods. One of the challenges for communities to experiment with new technologies including clean cooking is the various sources of risk that are ubiquitous in their lives. Many communities in low- and middle-income countries, including those in our study that are the focus of clean cooking technology interventions, rely on agriculture and informal labor markets for their livelihoods. Community members are uninsured against the multiple risks these livelihoods are subject to, such as monsoons, erratic rainfall and other risks. This inclines such communities to be risk averse, especially when it comes to investing in new technology and experimenting sufficiently with its use [46]. Therefore, the time to experiment and see the outcomes of a new technology before committing are significant processes influencing a household’s decision to adopt [47]. Not every household, however, need depend on their own experimentation. They benefit from the experience of other households that enables to them to make a commitment to new technologies [48, 49]. In a systematic review of the literature on adoption of ICSs, Rehfuess...
and colleagues [50] found that social influence was a major factor in swaying a household’s decision to take up clean cooking. In our study, we show that households communicate the perceived benefits of the new technology through word of mouth. Such a mechanism can both spread benefits or disappointment with new interventions. As we show in our study in the community that stopped using, multiple technical problems during the early stages resulted in fewer adoptees. Similarly, Agurto-Adrianzen [51] finds that in the initial stages of the adoption of ICSs, the number of adopters facing problems with the technology negatively impacted the household’s likelihood of adoption. Therefore, in the early stages of the roll-out of clean cooking, additional effort is necessary to ensure long-term use of the technology in that community.

System dynamics models provide a simulation platform to explore scenarios to develop insights about the system and inform program development. However, the scenarios are based on assumptions about the system and when these assumptions are no longer true the scenarios become invalid. The model suggests that, with adequate technical support, sustained use of a new technology is possible. However, the current model does not take into consideration the changing landscape of energy technologies. For example, what would happen if the households could access LPG? The community-based approach ensures that the assumptions in the model closely reflect the realities on the ground. LPG was not a factor for the communities in the study, and thus was not included in the model. This does not mean that in the near future LPG would not be a part of the energy mix of the households in these communities. In future studies, the boundary of the model can be expanded to include the influence of access to LPG on household decision making.

The results from a CBSD approach reflect the context of the community and the particular energy technology used by it. The results of this study may not be readily generalized to other settings. The goal would be to replicate this study in different community and technology contexts and understand what aspects of the model apply in different settings. For example the Urban Dynamics [52] model has been applied in several contexts including large cities like Boston to growing towns like Palm Coast, Florida [53]. For this model, the general process by which households transition from using traditional cooking technology, to stacking, and finally to predominantly using the new technology, could be applied in multiple settings. Similarly, processes like the word of mouth effect are well established in the diffusion of technology literature and could be applicable in other contexts. Finally, biogas was used as a representative technology to understand determinants of sustained use or abandonment of clean cooking systems. There might be other underlying factors that were not discussed during community engagement and consequently not accounted for in the model. Future studies could expand on the current work by testing how other variables would impact model behavior.

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