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Sustaining clean cooking: A system dynamics study of Ghana's rural LPG promotion program

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ABSTRACT

Household air pollution is a pervasive environmental health problem wherever access to cleaner fuels is poor. Despite numerous attempts to transition households away from polluting fuels, interventions are rarely sustainable. This intractability indicates that structural (i.e., systemic) dynamics act to maintain the status quo. In this case study of Ghana's Rural Liquefied Petroleum Gas (LPG) Promotion Program, our objectives were to 1) identify system structures affecting sustained fuel use, and 2) test strategies for improving intervention outcomes. To address these objectives, we applied a system dynamics approach, informed by a systematic literature review. A virtual simulation model was constructed to represent the implementation of the Rural LPG Program and its outcomes. By analyzing the model's structure and behavior, we proposed strategies that would improve the intervention's outcomes and tested the effectiveness of the strategies within the simulation model. Our results show that distributing two LPG cylinders to households (instead of one) contributed toward primary use of the fuel, whereas free weekly delivery of LPG (for up to four years) had limited long-term benefits and diminishing returns. Furthermore, reducing the time for users to perceive the benefits of cleaner fuels enhanced willingness-to-pay, and thereby helped to sustain higher rates of LPG use. This suggests that intervention planners should identify new users' expectations of benefits and proactively design ways to realize those benefits quickly (in a few weeks or less), while policy makers should support this as a design requirement in approval processes.

Introduction

Household air pollution remains a leading cause of death, particularly (though not exclusively) among low- and middle-income countries (Fuller et al., 2022; Rogalsky et al., 2014). Cooking and heating with cleaner fuels (e.g., electricity, ethanol, and liquefied petroleum gas (LPG)) lowers the burden of disease when compared to “polluting” fuels (unprocessed biomass, charcoal, coal, and kerosene) by reducing personal exposure to fine particulate matter ($PM_{2.5}$) and carbon monoxide (Chillrud et al., 2021; Qiu et al., 2019). The United Nations' Sustainable Development Goals (SDGs) promote a comprehensive and equitable transition to cleaner household energy, particularly through SDG 3, “ensure healthy lives and promote well-being for all at all ages,” and SDG 7, “ensure access to affordable, reliable, sustainable and modern energy for all.” Achieving this household energy transition would have positive implications for other SDGs as well (Rosenthal et al., 2018).

For a successful (i.e., health promoting) localized household energy transition, at least three major conditions should be met (Pope et al., 2017). First, households need reliable, convenient, and affordable access to cleaner fuel. Second, households must commit to primarily using cleaner fuels (stop using polluting fuels). Third, the first two conditions must be met for nearly every household in a specified area so that ambient pollution from some households does not limit the benefits of other households' cleaner air. These conditions highlight non-linear aspects of the household energy challenge. For example, the dose-response curve for $PM_{2.5}$ is such that major health benefits are only achieved at very low exposures (Burnett et al., 2014). This is why a single household's fuel mix must be almost entirely clean and why a critical “mass” of households must reduce their emissions.

Unfortunately, households amid an energy transition tend to use more than one fuel (and/or stove) type to fulfill different cooking, heating, or other purposes (known as fuel stacking), and this usually includes at least one polluting fuel (Gould et al., 2018; Rahut et al., 2017; Shankar et al., 2020). Household fuel choices are influenced by personal characteristics of the decision maker(s), such as education level and wealth (Menghwani et al., 2019; Owusu-Amankwah et al., 2023;

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Rahut et al., 2016), community factors like peers' fuel choice and population density (Shupler et al., 2019), and the national or sub-national enabling environment, including the relative cost, availability, and accessibility of different fuel options (Carrion et al., 2020; Puzzolo et al., 2019). Quinn et al. (2018) developed a logic model based on implementation science containing five interlinked dimensions related to scaling up clean fuel use. We believe that many interventions or policies aiming for an equitable and sustainable energy transition are unsuccessful when planners fail to consider these multiple dimensions (and scales) of household fuel choice and the interactions between them.

The complex characteristics described above (i.e., multi-dimensional, multi-scalar, and non-linear) highlight the applicability of *systems thinking* approaches for accelerating actionable learning about household air pollution (McAlister et al., 2022; Rosenthal et al., 2020). In systems thinking, the goal is to understand the systemic structure creating a problem in terms of component interactions, specifically, feedback relationships (Meadows, 2008). *Feedback* (a closed chain, or loop, of causal relationships) is an important structural mechanism that leads to well-defined behavior patterns. Many influential development organizations have researched and adapted ways of applying systems thinking to replace "conventional" approaches that are better suited for technical (routine) challenges (Huston & Moriarty, 2018; Lee et al., 2016; United Nations Children's Fund (UNICEF), 2016). However, a lack of consensus remains on systems thinking best practices, as do questions about broad feasibility (Walters et al., 2022; Wilkinson et al., 2018).

System dynamics, a modeling methodology rooted in the systems thinking paradigm, is particularly useful for visually and quantitatively representing feedback structures. The methodology also provides a means to test hypotheses about structural dynamics using computer simulation (Forrester, 2022). Researchers have used system dynamics to study major drivers of household air pollution in Nairobi's informal settlements (Dianati et al., 2019), factors and factor relationships influencing fuel choice in a South African informal settlement (Smit et al., 2019), and how various factors influence the transition to LPG in Nigeria (Shari et al., 2022). These studies were focused on the current and projected trends of cleaner fuel use in their respective contexts but not the structural causes of a past failed intervention. Reflecting on causes of failure can be a powerful mechanism for learning, leading to improved development practices (Vernon & Myers, 2021). For example, Chalise et al. (2018) sought to understand (using community-based system dynamics) why an intervention implemented in two similar rural Indian communities achieved sustained adoption of biogas in one, but not in the other. They found that on-demand technical support was integral to the intervention's success, but this may be a feature specific to biogas technology.

Our study contributes to existing literature by 1) demonstrating the practical use of the system dynamics methodology within sustainable development research, and 2) evaluating the systemic failure of a large-scale household energy intervention to inform recommendations for future interventions. Further, studying the Rural LPG Promotion Program in Ghana provided an opportunity to explore intervention sustainability for a case in which detailed information is available. This case is also important because 1) nearly 80 % of the population in Africa relies primarily on polluting fuels for cooking (more than double the percentage in any other World Health Organization region; World Health Organization (WHO), 2023), and 2) LPG is regarded as one of the most viable energy alternatives for this context with large potential benefits to both health and climate (Floess et al., 2023). Hence, insights gained are expected to be applicable to other locations.

Like many other countries in sub-Saharan Africa, almost 90 % of rural Ghanaian households primarily use polluting fuels for cooking (WHO, 2023). This contributes to multiple detrimental health outcomes; in Ghana, stroke, lower respiratory infections, and ischemic heart disease are all in the top five leading causes of death for both female and male adults (WHO, 2023). Additionally, time spent on collecting firewood (approximately 30 min per day where firewood is "abundantly available;" Prah et al., 2020) could become even more burdensome as forests are converted into agricultural land (Acheampong et al., 2019). From 2013 to 2017, the Ghanaian government implemented the Rural LPG Promotion Program, aiming to expand the use of LPG in rural areas. They distributed one (one-burner) LPG stove and one fuel cylinder to approximately 150,000 households in about one third of the nation's districts (Adjei-Mantey et al., 2021). In a sample of 200 recipient households, the rate of LPG use decreased to less than 5 % in the first nine months after receiving the stove (Abdulai et al., 2018). When the intervention was replicated at a smaller scale with modifications (targeted health promotion, on-demand LPG delivery) LPG use was only marginally more sustained and fuel stacking persisted (Carrion et al., 2021). Others have concluded that LPG cost and poor access (i.e., distance to refill stations) were barriers to a successful program (Abdulai et al., 2018; Asante et al., 2018; Carrion et al., 2021). However, despite the recognized complexity of addressing household air pollution, these explanations are indicative of linear cause-and-effect thinking; in contrast, we sought to understand why the Rural LPG Promotion Program failed from a systems thinking perspective.

Therefore, this study employs system dynamics to meet the following objectives: 1) to develop a dynamic hypothesis about the system structures that caused the Rural LPG Promotion Program in Ghana to fail, and 2) to recommend potential improvements to the intervention design. Our study also serves as an example of how researchers and intervention planners can apply system dynamics to reflect on environmental health intervention outcomes and better understand their structural (systemic) causes. Finally, based on our model analyses and simulation results, we recommend several areas for future research to support sustainable household energy transitions.

Material and methods

The system dynamics methodology follows an iterative process that typically starts with problem articulation and ends with strategy formulation and evaluation (Sterman, 2000a).

Problem articulation

Despite achieving widespread distribution of LPG stoves, the Rural LPG Promotion Program failed to motivate sustained adoption among recipient households (Adjei-Mantey & Takeuchi, 2022). Sustained adoption is defined as "the phase when the cleaner cooking technology is used for [an] extended period of time, is in working condition, meets the user's needs, and [the] user has willingness-to-pay in maintaining or repurchasing it" (Kumar & Mehta, 2016). We characterized the outcome of the Rural LPG Promotion Program as a behavior-over-time reference mode, with the portion of household cooking done with LPG as our main variable of interest. This reference mode can be stated as "LPG use gradually decreased from 40% in the first week to less than 5% after 9 months" (Abdulai et al., 2018), and approximates other observations of the Rural LPG Promotion Program presented in the literature (see Asante et al., 2018; Carrion et al., 2020). A graphical representation of the reference mode is provided in Fig. A1 in the Appendix.

Dynamic hypothesis

To develop a hypothesis about the structure leading to the observed reference mode behavior, we began by compiling a list of key variables. These variables were identified via a systematic literature review related to LPG use in rural Ghana. We searched the Scopus database for peer-reviewed, English language articles containing "Ghana," "rural," "LPG," and "cook*" in the title, abstract or keywords. The scope of this systematic review was intentionally narrow and specific to rural Ghana and LPG. We did this to ensure that the factors we identified were relevant explanatory variables for the observed reference mode. Other literature related to LPG use and household energy more broadly (and in different contexts) were consulted throughout model development and interpretation of results. This helped us to build confidence in the model structure and to detect (and rectify) model behaviors that were contrary to common knowledge about household energy transitions.

The systematic search and screening process resulted in nine articles that identified factors acting as barriers or enablers of cooking with LPG. We extracted these factors (total = 82, average per article = 9), and then coded them thematically and iteratively to reduce the list to key variables (Bernard, 2017). For example, the "presence of skilled technicians" and "availability of spare parts" were both coded as "LPG repair accessibility." In total, 13 key variables were identified, shown in Table 1. See Fig. A2 in the Appendix for the systematic review flowchart and Table A1 for the list of nine articles (readers may also refer to these for more details about rural LPG use in Ghana).

Using the key variables as the main elements of our model, we hypothesized how they might have been connected via feedback relationships to produce the reference mode. For example, feedback may be *reinforcing*, which means that it results in ever-increasing growth or decline of a variable, or *balancing*, which means that it dampens a variable's rate of change. In developing this dynamic hypothesis, we iterated between a qualitative conceptual model (causal loop diagram), and a quantitative simulation model (stock-flow model). The latter helped to test our assumptions, and the former kept us focused on fundamental, explanatory dynamics by distilling the simulation model into a relatively simple diagram. Importantly, all the stocks in our model are interconnected via feedback processes. These relationships explain the behavior observed during the nine months after LPG stove distribution.

First, there are two balancing feedback loops involving households' use of LPG and their available cash (see Fig. 1B). As households spend more money on LPG refills and repairs, they have less cash available for using LPG. We assume that other household expenses remain the same regardless of whether households are using LPG, and that the cost of alternative fuels (most often, firewood) is negligible. On the other hand, when a households' cash is running low, they are more likely to ration LPG and increase their use of cheaper fuels. This is reflective of fuel stacking, where LPG is used sparingly (due to its relatively high cost) for certain cooking tasks (e.g., reheating leftovers).

In addition to cash availability, a household's decision to use LPG depends on their willingness-to-pay. Some benefits of cooking with LPG may be experienced almost immediately (e.g., time savings, no smoke in eyes). However, these benefits seem to be outweighed by factors like cooks' comfort with traditional three-stone fires (versus unfamiliarity with and concerns about LPG stoves), and the inconvenience of traveling to LPG filling stations (25 km, on average) (Abdulai et al., 2018; Asante et al., 2018). Therefore, we assumed that sustained adoption eventually affects willingness-to-pay, given enough time (see Fig. 1C). For example, LPG adopters may perceive a reduction in respiratory infections in their household (and other health improvements), but this is not likely to happen in the near term. Likewise, if LPG suppliers perceive an increased demand for LPG in rural areas, they will likely increase distribution points, making LPG more convenient for households. This process has inherent delays, both in suppliers' perception of demand and in the expansion of distribution networks (we have lumped these together as "market delay" in Fig. 1). It is important to note that in addition to delays, both reinforcing processes rely on a critical mass of community members consistently using LPG as their primary cooking fuel; suppliers will not respond to just a few households, and ambient air quality in a community is affected by all households' fuel choices.

Finally, the accessibility of LPG filling stations, repair parts, and technicians all affect the total cost of using LPG. If LPG suppliers respond to demand changes, these are reinforced (after delays) by consequential changes in the cost of LPG (see Fig. 1D). For example, if more filling stations were established closer to rural communities (or if suppliers found house-to-house delivery to be lucrative), then the cost to households of transporting cylinders for refill would decrease. Changes in the total cost of LPG affect both affordability and, if households are actively using LPG, the amount of cash they have available for spending.

Table 1
Key variables identified as barriers or enablers of cooking with LPG in rural Ghana.

Key variable	Examples	n[a]
LPG fuel cost	Fuel price, transport price	7
LPG refill accessibility	Distance to filling stations (skids), reliability of supply, filling logistics	6
Stove preferences	Suitability of three-stone fire for common dishes, comfort with and knowledge of using stove, speed of cooking with LPG	6
Accessibility of other fuels	Biomass availability, seasonal effects on fuel wood, electrical grid	5
Household size	Number of people in household	5
LPG safety concerns	Fear of burns, fires, and explosions	5
Seasonality of income	Liquidity constraints, subsistence lifestyle, cash on hand, use of credit, off-farm employment	5
Cost of other fuels	Biomass price, price of alternative fuels (kerosene, charcoal), time cost of collecting fuel wood	4
Household head characteristics	Gender, age, whether household head is primary cook	4
Income	Economic well-being, wealth status	4
Education	Educational attainment, level of education (primary, secondary, tertiary)	3
LPG stove cost	Stove price, price of spare parts and repairs	3
LPG repair accessibility	skilled technicians, spare parts, maintenance capability	3

[a] Number of articles that contained each variable.

Model formulation

Equations and relationships

The stock-flow (simulation) model was built using Vensim DSS software (https://vensim.com/software/). First, we designated "households with usable LPG stove" as a stock – that is, as a function of time following the form of Eq. (1).

$$Stock(t) = \int_{t_0}^{t} (Inflows - Outflows)dt + Stock(t_0) \tag{1}$$

The equation represents a material balance governing the accumulation of the stock over the time interval t_0 to t; it is based on the principle of conservation of mass in the physical sciences (see Eqs. (5.3-2) in Forrester, 2022). Next, we added the in- and outflows controlling the stock and connected these to other stocks or to quantities outside of the system boundaries (i.e., sources or sinks). Flows are rates, meaning that their units equal the units of a stock divided by a unit of time. Other key variables from our conceptual model (Fig. 1) were also designated as stocks if accumulation (or de-accumulation) was an important property of their behavior. For example, households' available cash, a quantity with imbalanced and variable in- and outflows, was designated as a stock. Each additional stock was added to the model like the first, by designating its flows and connecting these to sinks, sources, or other stocks. Building the model outward from the stocks and flows, we added explanatory (auxiliary) variables to define each flow. From there, our objective was to logically connect the key variables according to the feedback relationships in our conceptual model. We added any necessary constants or dimensionless multipliers (all with real-world meanings) to ensure that the simulation model was dimensionally consistent.

The stock-flow structure for household LPG stove status is shown in Fig. 2. The stocks represent a closed system so that the total number of households remained constant throughout a simulation. This structure allowed us to track how the usability of LPG stoves changed for recipient households, which start in the "households without LPG stove" stock. Factors affecting the flows can be constant parameters or "auxiliary" variables that change due to other variables and parameters in the

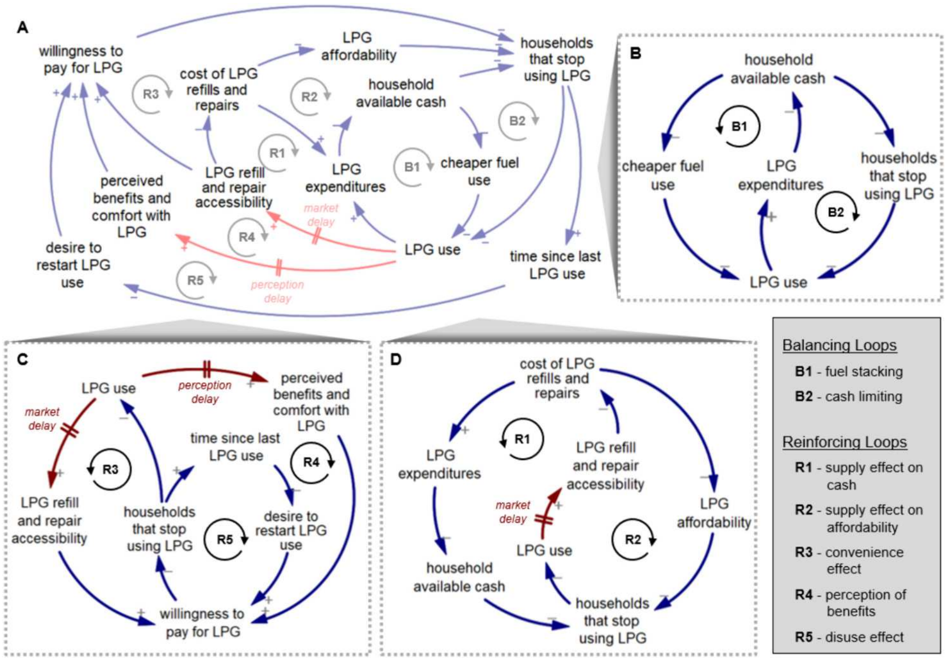

Fig. 1. Causal loop diagram depicting the endogenous structure of the model (A). Pieces of the structure are separated into parts (B), (C), and (D) for clarity. Arrows with plus signs (+) indicate direct causal relationships, arrows with minus signs (−) indicate inverse causal relationships, and slash marks (||) across an arrow indicate delays.

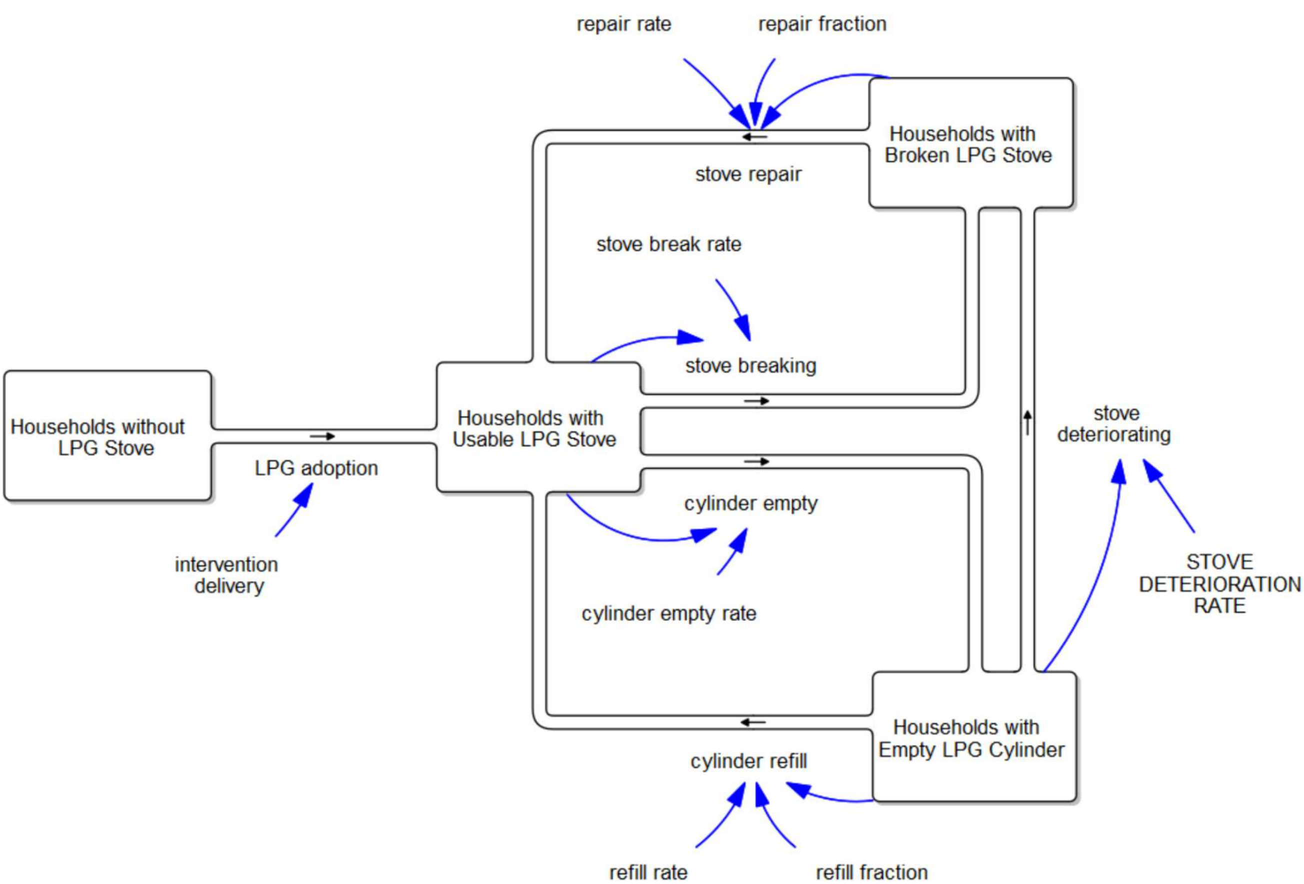

Fig. 2. Stock-flow structure for households' LPG status, showing immediate causes only. Stocks are shown in boxes, flows are represented by "pipes" connecting the stocks, auxiliary variables are in all lowercase letters, and constant parameters are in all UPPERCASE letters.

model. For example, "stove deterioration rate" is a constant parameter, while "cylinder empty rate" is an auxiliary variable that is dependent on households' available cash. The stock-flow structures for other stocks (willingness to pay for LPG, available cash, and distance to refill or repair) are shown in Figs. A3–5. All model equations and parameters are provided in the Supplementary Materials.

Parameterization and calibration

The model uses the Euler integration technique with a time step of 0.25 weeks. The basic version of the model contains 36 constant parameters (i.e., inputs). Of these, seven are "true constants," such as the "year duration" parameter (52 weeks/year), and four were prescribed by the specific scenario we wanted to simulate – that is, an intervention in which stoves were distributed to 200 rural households (initial households with LPG = 0, initial households without LPG = 200) in a four-week period (intervention start = 0 weeks (beginning of simulation), intervention duration = 4 weeks). Of the remaining parameters, we located real-world data for eight from the Ghana Statistical Service and relevant published literature (see Table S6 in the Supplementary Materials) and used the same sources to estimate five more. Finally, there were 12 parameters with unknown values. These parameters were calibrated during model testing using the SyntheSim function in Vensim DSS. SyntheSim allows the modeler to adjust parameter values along a scale, either one at a time or simultaneously, to see their effect on the model output. The goal of this preliminary calibration was to find a set of reasonable parameter values for which the model reproduced the reference mode behavior.

Model testing

System dynamics models are considered useful when they meet the following conditions: (1) the model elements and relationships have real-world meanings and are consistent with observations, (2) the model endogenously generates the qualitative reference mode behavior (is not primarily data-driven), (3) the model behavior is plausible when simulated under extreme conditions, and (4) sensitive model parameters are also sensitive in the real world (Meadows & Robinson, 2007). We employed several model tests per Sterman (2000b) and Turner (2020) to evaluate whether our model met the above conditions (see Table A2). These tests were performed iteratively while developing the stock-flow simulation model. Through sensitivity analyses, we determined the most sensitive unknown parameters and graphical functions. To demonstrate uncertainty in the model results, for subsequent scenarios we performed multiple simulations ($n = 500$) while varying these parameters randomly within assigned ranges and assuming independent uniform distributions (see Table A3 and Fig. A6).

Results and discussion

Model performance

Behavior reproduction

The model reproduces the behavior trend observed in the nine months following the Rural LPG Promotion Program. Fig. 3 shows the "Base Run" simulation results, highlighting changes in the average portion of cooking done with LPG (which can be compared to the reference mode in Fig. A1), and the behavior of stock variables over the same period. The model structure and parameterization of the Base Run represent the conditions that, according to our dynamic hypothesis, led to the failure of the Rural LPG Promotion Program. The simulation time was one year (52 weeks) to encompass the assumed four-week period in which stoves were distributed and the following nine months (39 weeks), as well as seasonal variations in households' available cash. At the end of the stove distribution period, LPG was used by households for about 40 % of their total cooking needs (on average), dropping to around 5 % nine months later. There was a slight increasing trend between weeks 26 and 30, which can be attributed to households having more cash available during that time of year, but this trend was not sustained.

Extreme conditions

In this study, we used extreme conditions testing to effectively "turn off" feedback loops, which helped us to understand the relative strength of the loops in the period during and just after stove distribution. For example, we wanted to know how the model behavior would change if households had more than enough cash for LPG expenditures (i.e., if

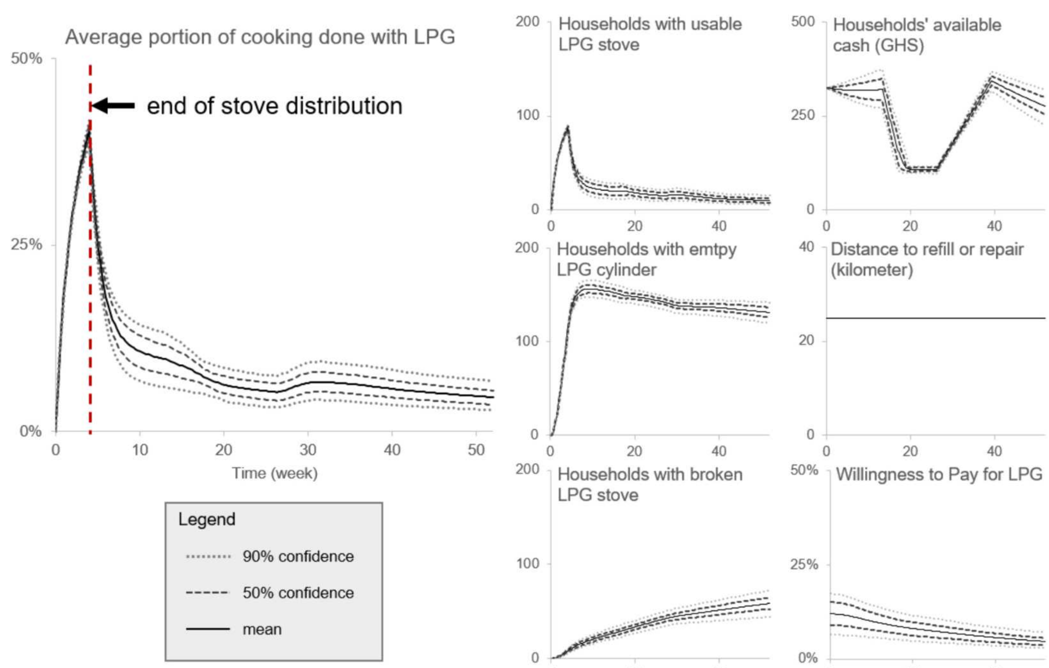

Fig. 3. "Base run" simulation results showing the average portion of cooking done with LPG (as a percentage of total household cooking) and main stock variables over the same period (one year). Intervals are shown for 50 and 90 % confidence levels based on uncertainty in selected model parameters and graphical functions.

cash were plentiful). By manipulating cash-related parameters (initial available cash, income) so that they were much higher than the Base Run scenario, we effectively eliminated the feedback loops containing households' available cash (B1, B2, and R1 in Fig. 1) because the stock of available cash was no longer affected by changes in other model variables. In addition to testing the extremes of households' cash availability (from plentiful to non-existent), we also explored extreme conditions related to LPG refill and repair accessibility and households' willingness-to-pay.

We tested these extremes separately (Fig. 4B and C) and simultaneously (Fig. 4A). Table A4 contains a list of the parameters that were altered for each test and their values. All other parameters were the same as in the Base Run simulation. The simultaneous tests were designed according to a matrix of extreme "high" (best case) and "low" (worst case) conditions for each of the three variables, which resulted in eight unique scenarios. For example, in the first scenario, all the variables were in the "high" condition (plentiful cash, refills and repairs readily accessible, and 100 % willingness-to-pay). In the next three scenarios, two variables were in the "high" condition, and one was in the "low" condition. The rest of the matrix continued in this fashion (shown in its entirety in Table A5), with the final scenario having all variables in the "low" condition (no cash, refills and repairs inaccessible, and no willingness-to-pay). Interestingly, these eight scenarios produced only three unique behaviors for the average portion of cooking done with LPG, which are shown in Fig. 4A.

Based on the results presented in Fig. 4A and C, if households had cash available, but refills (or repairs) were inaccessible or willingness-to-pay was zero, then LPG use quickly dropped from just under 40 % to near zero following the stove distribution period. This can be attributed to limited or non-existent LPG rationing (loop B1 in Fig. 1), so that the fuel supplied to households was quickly used up, but households either had no ability or no desire to refill their supply. On the other hand, if households did not have any available cash, then the status of refill and repair accessibility or willingness-to-pay had no effect on LPG use. In these scenarios (also shown in Fig. 4A and C), LPG use only rose to about 15 % by the end of stove distribution, but then decreased to near zero more gradually than the previous case. This makes sense because LPG rationing was high, which decreased the rate of households' fuel use. However, without any means to purchase LPG, each households' supply eventually ran out.

We also learned from the extreme conditions testing that for Base Run conditions, increasing households' willingness-to-pay had the greatest potential to sustain LPG use compared to increasing households' available cash or LPG refill and repair accessibility (Fig. 4B). It is worth noting though, that the seasonal variation in households' available cash had a greater effect on LPG use when willingness-to-pay was high. This was because more households were using LPG, which increased their expenditures on LPG and thus depleted cash reserves. Therefore, rationing increased (B1) and slowed the rate of LPG use (but maintained higher numbers of users), while cash limitations decreased the number of users (B2). This balancing action eventually increased cash availability by decreasing LPG expenditures, thereby allowing more households to use LPG. The resulting oscillating behavior is apparent in Fig. 4B for willingness-to-pay at 100 % and the reinforcing feedback loops containing willingness-to-pay (R3, R4, and R5) "turned off." If willingness-to-pay for LPG were affected by changes in other model variables (i.e., if R3, R4, and R5 were "on"), then these reinforcing loops would likely reduce willingness-to-pay as soon as households ran out of cash to purchase LPG, or when households experienced the inconvenience of traveling long distances to refill their supply or repair a broken stove.

Finally, in Fig. 4A, we see that even when all the (tested) barriers to LPG use are eliminated, the average portion of cooking done with LPG was only maintained around 60 %. We believe that this was due to

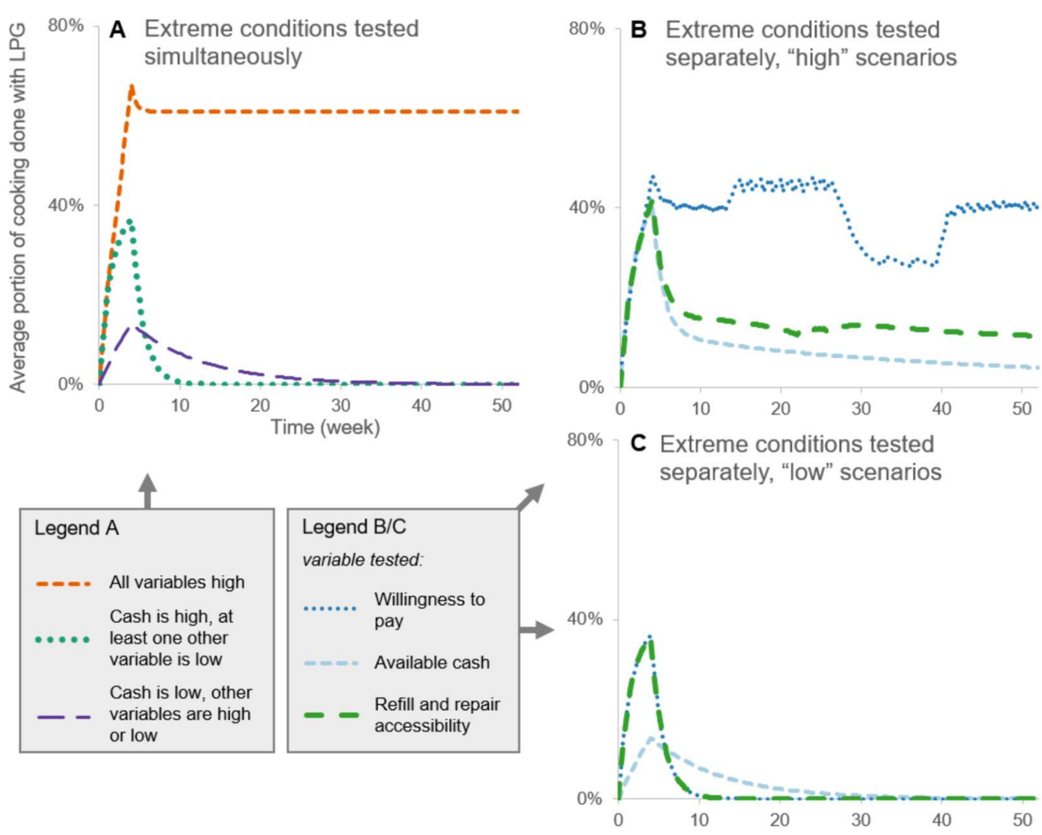

Fig. 4. Results of extreme conditions simulations. All plots show the model output for "average portion of cooking done with LPG" (as a percentage of total household cooking) over the same period (one year). "High" scenarios represent the extreme best-case conditions, while "low" scenarios represent the extreme worst-case conditions.

inherent delays in refilling an empty LPG cylinder or repairing a broken LPG stove, requiring households to maintain the use of other stoves to continuously fulfill their cooking needs. This theory provided the basis for the first focus of our strategy testing, described below.

Strategies for sustained adoption

Number of stoves and cylinders

Based on a recent study in India (Harrell et al., 2020), we hypothesized that increasing the number of cylinders and/or stoves available to a household would allow continued use of LPG while one cylinder or stove was being refilled or repaired. To test this theory, we simulated model scenarios in which additional cylinders and/or stoves were distributed per household.

First, we assumed that the need to refill a depleted LPG cylinder typically arises much sooner than the need to repair or replace a stove component (consistent with the calibrated model parameter values, Table S6). (Examples of LPG stove maintenance include ball valve replacement, rubber hose replacement, and leak troubleshooting and repairs; Clean Cooking Alliance et al., 2022.) Therefore, in our first strategy test, we increased the number of LPG cylinders received by each household to two instead of one. This required some alterations to the model structure, including the addition of a stock variable, "households with two empty LPG cylinders" (see Fig. A7). In this new structure, households with one empty LPG cylinder could still cook with LPG. We further assumed that the rate of emptying the first cylinder was not dependent on households' available cash (i.e., was constant), but the rate of emptying the second cylinder was dependent.

The simulation results show a dramatic effect on the *potential* for increased LPG use. In Fig. 5, the two-cylinder model yields a maximum "average portion of cooking done with LPG" that is about 25 % higher than in the one-cylinder model (Base Run). However, the same feedback loops acted on households' available cash and willingness-to-pay for LPG, quickly driving down LPG use. By week 20 of the simulation, the gains of the two-cylinder model were only marginal.

We also tested an intervention in which two stoves and two cylinders were distributed to each household, meant to counteract downtime when a household's stove needs repairs (see Fig. A8). The additional stove had only a slight effect on the model output, increasing LPG use by less than 5 % from the two-cylinder, one-stove model (see Fig. 5).

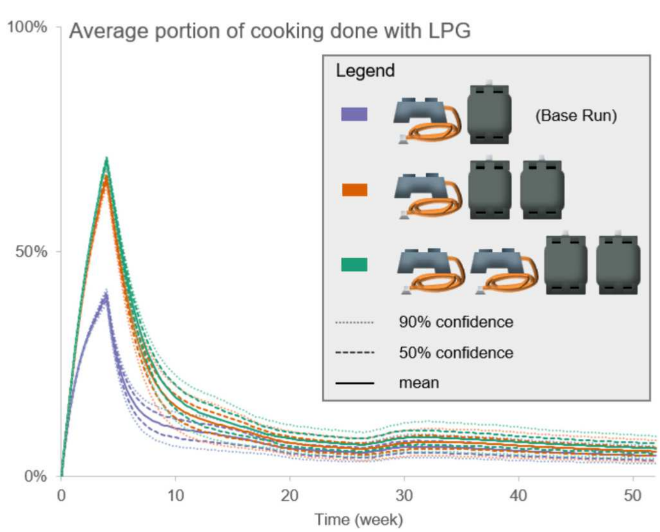

Fig. 5. Model output for "average portion of cooking done with LPG" when households receive one LPG stove and one cylinder (Base Run), one LPG stove and two cylinders, and two LPG stoves and two cylinders. Intervals are shown for 50 and 90 % confidence levels based on uncertainty in selected model parameters.

Willingness-to-pay

In the extreme conditions tests, we found that increasing households' willingness-to-pay for LPG yielded greater benefits than increasing refill and repair accessibility or households' available cash. Therefore, we selected "willingness-to-pay for LPG" as the next focus of strategy testing.

To develop a strategy that maximizes willingness-to-pay, we searched for parameters that might feasibly be adjusted during an intervention. Of the parameters that most directly affected willingness-to-pay (perception delay, disuse factor, and initial willingness to pay), perception delay – the time between households using an LPG stove and their perception of benefits – was the likeliest intervention point. Initial willingness-to-pay represents a pre-existing condition, and regardless, had a limited effect on long-term LPG use when altered from one extreme to another (0 to 1). The disuse factor, which affects the rate that willingness-to-pay decreases after households stop using LPG, was already a relatively low (favorable) value in the Base Run scenario, indicating little room for improvement. In contrast, the perception delay for the Base Run scenario was 260 weeks (5 years), an unfavorable value with considerable room for improvement.

Using the SyntheSim function in Vensim DSS, we searched for a threshold value of the perception delay that reversed the decreasing trend in "average portion of cooking done with LPG." We found that the trend in LPG use leveled off at about 5 %, rather than continually decreasing, when the perception delay was 16 weeks. For shorter perception delays, LPG use gradually increased. Fig. 6 shows the results for perception delays of 16, 4, and 1 week(s), with all other parameters consistent with the one-stove, two-cylinder scenario.

The results with a one-week perception delay are promising, with sustained use of LPG approximately 28 % higher than the maximum use from the Base Run. However, these results still exhibit a decrease of approximately 30 % in LPG use just after the initial stove distribution period. Also, with greater LPG use, households' available cash was lower on average. Unintended consequences could include the lost opportunity to use available "spending money" on other items (e.g., drinking water, food, school fees). Furthermore, higher rationing was indicated, meaning that households are less likely to use LPG as their primary cooking fuel and more likely to supplement with cheaper, dirtier fuels like firewood.

Finally, there is the important implementation challenge of *how* to achieve a shorter perception delay. We are not aware of any interventions that have specifically targeted the delay between using an LPG stove and perceiving benefits. According to behavior change theories, households' motivation (akin to willingness-to-pay) in the "during" phase of cookstove adoption (after households acquire a new stove) can be supported by reinforcing the idea that "the stove can help meet personally defined goals" (Jürisoo et al., 2018). Therefore, we believe that intervention planners should strive to understand households' expectations about how using their LPG stove will benefit them, so that these aspirations can be reinforced regularly.

Free deliveries

In a controlled trial in Peru, households that received free LPG deliveries for one year were more likely to continue using LPG during the following year (Williams et al., 2023). Though a similar intervention in Ghana had less success (Carrion et al., 2021), we tested this strategy within the model, to understand how it might complement an intervention targeting willingness-to-pay. In simulations where the perception delay was unaltered, the free weekly delivery strategy had little effect. Therefore, we simulated the one-stove, two-cylinder model while varying the duration of the free delivery period and the length of the perception delay (using 1 week, 4 weeks, and 16 weeks, as before). Although we simulated several different durations of the free delivery period (using SyntheSim), results shown in Fig. 7 span a reasonable range of potential intervention designs and allow comparison to the one-year trial in Peru.

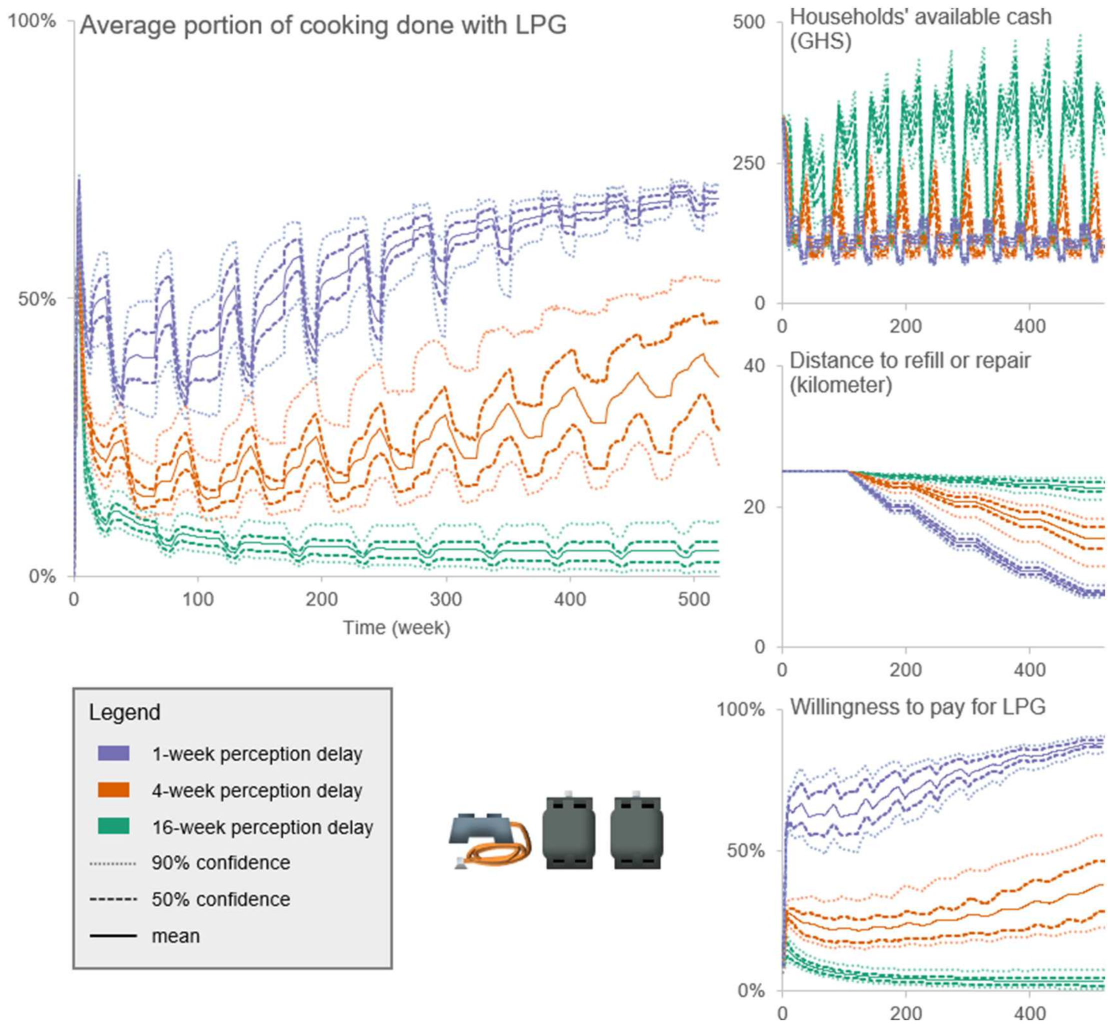

Fig. 6. Simulation results for different perception delays when households receive one LPG stove and two cylinders. Results are given for "average portion of cooking done with LPG" as well as selected stock variables over a 520-week (10 year) simulation period.

The results suggest that one year of free weekly LPG delivery has a positive effect on LPG use during that year but has a minimal effect on long term LPG use (i.e., at ten years). Two years of free delivery produced only marginally better results. Four years of free delivery unsurprisingly had the greatest effect on long term LPG use, but interestingly, we found that the four-year delivery period was the most impactful when the perception delay was four weeks. With a one-week perception delay, the four-year free delivery period had little effect on the long term (ten year) outlook for LPG use, whereas there was about a 20 % increase in LPG use in year ten with the four-week perception delay (compared to having no free delivery). This indicates, reasonably, that there are diminishing returns for providing free delivery as LPG accessibility increases "naturally" due to higher demand (R3 in Fig. 1).

Limitations and future research directions

Models are always simplifications of reality, with requisite boundaries that exclude potentially relevant factors, relationships, and dynamics. For instance, we did not capture seasonal differences in the amount of cooking done at home (e.g., in Northern Ghanaian households participating in the REACCTING study, there were noticeable fluctuations in stove use at the end of the rainy season; Piedrahita et al., 2016). Similarly, we did not include seasonal changes in biomass availability or quality; rather, we assumed that households could always decide to cook with fuels that were cheaper and easier to access than LPG.

Additionally, system dynamics models have a particular limitation in that they are highly aggregated. We lumped together into "stocks" heterogenous groups of people with different resources, needs, and desires, and parameterized the model with average values for factors like income, perception time, and willingness-to-pay. This limitation has led some researchers to pair system dynamics with more disaggregated methodologies, such as agent-based modeling (e.g., Altarabsheh et al., 2019; Taghikhah et al., 2021). Hybrid models are certainly a potential option for future research in household energy transitions.

Despite these limitations, we built confidence in our model through rigorous testing. *Because* the model is a simplified version of reality, we were able to clearly connect model behaviors to the model structure. Additionally, through sensitivity analyses, we identified some uncertain factors and relationships that potentially have substantial effects on households' decisions to cook with LPG. While we represented this uncertainty with confidence intervals in our results, future research could be directed toward these factors and relationships. For example, how much does stopping LPG use affect households' future decisions to start using it again? (We named this the "disuse factor," which acts on loop R5 in Fig. 1.) Also, what is the relationship between stove use and the need for stove maintenance? Does it increase linearly? Exponentially? We assumed that there is a constant "stove deterioration rate" which implies that stoves that are not in use eventually need repair. What is that rate? Could it be slowed if households were given a cover or locker for storing

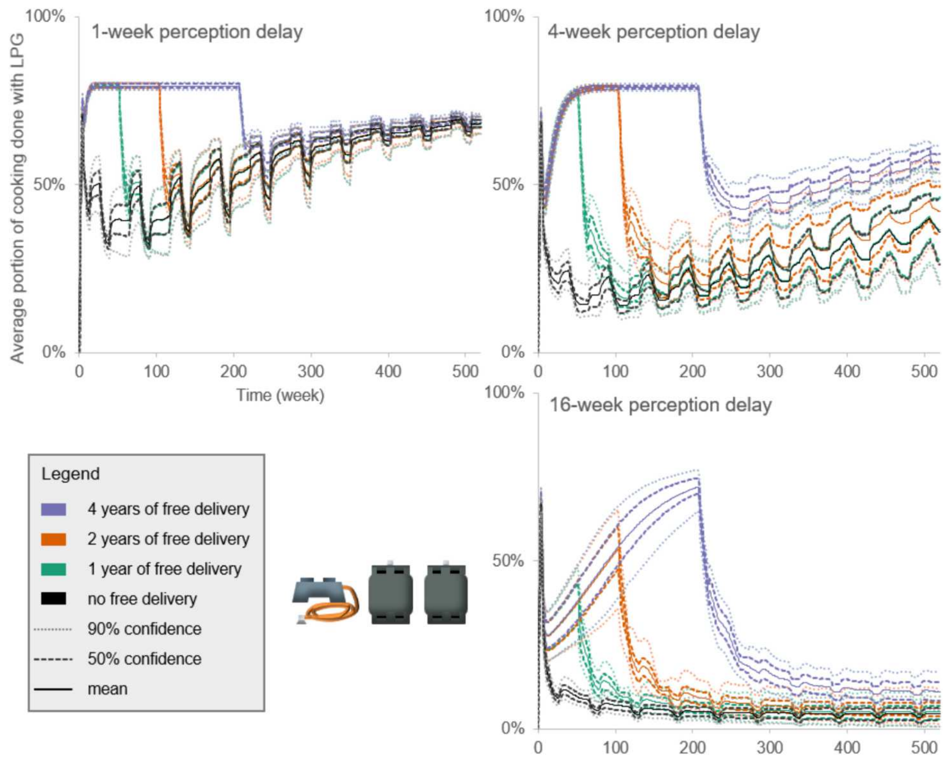

Fig. 7. Simulation results for different free delivery periods with different perception delays when households receive one LPG stove and two cylinders. All results are for “average portion of cooking done with LPG” for 520 weeks (10 years).

their stove while not in use? We believe that a strength of the system dynamics approach is that all such assumptions must be explicitly stated to develop a working simulation model, thus exposing gaps in existing knowledge which may have been harder to identify in mental models alone. Therefore, we recommend that intervention planners consider developing simulation models that test their assumptions, both about the reasons behind observed trends and expectations about how potential strategies might enact change.

Conclusions

In this case study, we were able to reproduce and explore long-term LPG use behavior with system dynamics modeling. The structural and dynamic understanding led to an explanation for why a large-scale rural LPG program failed and how to improve the effectiveness and sustainability of future interventions in similar contexts. When considering broad intervention leverage points (willingness-to-pay, available cash, and refill and repair accessibility), willingness-to-pay had the greatest influence on sustaining high percentages of LPG use. Greater refill and repair accessibility also improved outcomes from the status quo, though less so. Implementing free weekly delivery service was effective in supporting LPG use but had minimal effects in the long-term (after the free delivery period ended). Distributing two LPG cylinders to households (instead of one) increased short-term LPG use by 25 %. However, the effects of this strategy alone were marginal after 20 weeks, indicating that a multi-faceted intervention strategy is likely necessary to maximize sustained LPG use. When providing households with two cylinders and shortening the delay in the perception of benefits to one week, LPG use was sustained in the long-term (ten years) at over 50 %, indicating primary use of LPG over other fuel types. This appears to be the most promising intervention direction.

It follows that intervention planners should conduct context-specific research to understand LPG adopters' expectations of benefits, and then design intervention practices that help reinforce those beliefs. This might be accomplished through household surveys, interviews, or similar explorations of consumer's perceptions and preferences regarding LPG. Policy makers should support and perhaps require this type of research before approving proposed household energy interventions. Theoretically, the reinforcing process between the expectation and fulfilment of benefits is self-sustaining; the more that users realize the benefits of LPG (as opposed to the cost and inconvenience), the more they will be willing to pay for it, and the more convenient and affordable it is expected to become.

CRediT authorship contribution statement

Martha M. McAlister: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **James R. Mihelcic:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Amy L. Stuart:** Writing – review & editing, Validation, Supervision, Methodology, Investigation. **Qiong Zhang:** Writing – review & editing, Validation, Supervision, Software, Methodology, Investigation, Funding acquisition, Conceptualization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2024.101497.

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