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Perspective

Addressing Energy Poverty in India: A systems perspective on the role of localization, affordability, and saturation in implementing solar technologies

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ABSTRACT

Decentralized solar photovoltaic (PV) systems have emerged as an option in unelectrified rural areas for clean lighting and reduced kerosene use. Despite benefits, there are significant barriers to implement and sustain solar PV systems because of inadequate understanding of the feedback between adoption, diffusion, and implementation processes in resource poor communities of low and middle income countries. We analyze the social-behavioral and solar lamp assembly and distribution processes involved in implementing a million solar lamps in rural India and present a novel system dynamics framework to understand solar lamp technology implementation in India and other countries of South Asia. Our framework of three inter-locked subsystems – Localization, Affordability, and Saturation – explains how localization, affordability, and saturation emerge from a structure of feedback mechanisms and interact to drive adoption and sustained use of solar PV systems in resource poor communities. A system dynamics approach highlights the importance of understanding feedback and interdependence of these factors, provides tangible insights for future decentralized solar lamp and solar home product deployments.

1. Introduction

Around 1.2 billion people in the world lack electricity, 244 million of which are in India [1]. Most reside in low-income households in geographically dispersed rural areas. Many households are dependent on inefficient kerosene for lighting [2–5]. Indoor kerosene combustion without proper ventilation poses significant health risks including pulmonary disorders and dermal ailments [6–8]. Kerosene byproducts also contribute to climate altering black carbon emissions [9–11]. Common kerosene based products are also inefficient requiring households to purchase large quantities. To help mitigate fuel costs, the Indian government subsidizes kerosene resulting in perverse kerosene use regardless of the fuel's adverse health and environmental effects [12,13].

At the same time electricity is inaccessible, expensive, and an unreliable lighting and energy alternative for rural households. Although there have been efforts by the Indian government to increase rural electricity access, the electrification rate remains much lower in rural than in urban areas [14,15]. Conventional thermal power plants are unable to meet growing demand due to environmental, infrastructural, and financial limitations [16]. Enhancing current production capacity using power plants would take time and require significant financial investment to provide electricity to remote areas [16–18]. Rural areas that are able to gain access to the electrical grid still face challenges. Since most households are unable to afford electricity, distribution companies give low priority to rural areas. As a result, grid-based electricity is unreliable and frequently suffers power shortages. The Electricity Supply Monitoring Initiative (ESMI) found that only 16% of electrified rural households receive the entire six hours of electricity supply during the evening hours between 5 pm and 11 pm [18].

As conventional approaches fall short, rural households need an energy source that is decentralized, affordable, reliable, and clean to meet their growing demand and aspirations.

2. The solar alternative

Solar PV technology offers an immediate lighting solution for rural households with limited or no access to electricity. Advantages of solar PV include decentralized availability capable of reaching remote areas, easy management, sufficient light output, portability for indoor and

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outdoor domestic lighting, and no indoor pollution [19–21]. Given the potential of solar PV technology, the Indian government has launched various solar PV initiatives since the 1980s, including the National Solar Mission in 2010. Despite these efforts, penetration of solar PV technology remains below 1% in India [22]. Between 2010 and 2016, only 996,841 solar lamps and 1,396,036 solar home lighting systems were installed through various programs [23]. Moreover, lack of a variety of solar products in rural markets make it difficult for households to access off-grid solutions. Low market access also limits awareness of solar technology and its benefits [20,24,25]. This limited progress implies greater efforts are needed to understand the barriers to solar implementation to promote access and uptake across regions.

2.1. Barriers to solar PV

The literature points to a variety of barriers to diffusion and adoption of solar PV including technical, social, and financial factors [26]. High installation costs make off-grid solar products expensive for the rural poor and limit their ability to purchase them with the help of financial subsidies [24,25,27]. Generating confidence in technology remains a challenge due to quality and performance issues. Some devices are difficult to use resulting in breakages, lowering confidence in the technology. Unreliable after-sales repair service or lack of instruction on proper usage leads to a higher number of non-functional solar lamps within the warranty period or life cycle of the product [24,25,28,29]. Chaurey et al., observe that without the diffusion of repair and maintenance skills in local communities, solar PV cannot be sustained [30]. Even if after-sale services are available, some have found that when solar products are provided at reduced cost through subsidies there may be little incentive for users to invest in maintenance [20]. Social factors also play a role in spreading mistrust in the technology and skepticism of the value of energy savings [29,31]. Some suggest involvement of local communities as a way to overcome these barriers to adoption of solar technology at scale [30,32,33].

2.2. Complexity of rural solar implementation

While the literature points to some barriers to solar implementation, little is known about how enablers and barriers interact in the context of a local rural community. We use a system dynamics lens to explore enablers and barriers to implementation and uptake of solar lamps, a clean energy technology, in the Million Solar Study Lamps Program.

System dynamics (SD) utilizes qualitative causal maps and quantitative simulation models to illustrate and understand complex systems from a feedback perspective [34]. SD provides insights into the underlying structure and connections between components that generate system behavior. There is a convention of using SD to derive insights into project implementation as well as formulate dynamic hypotheses to explain complex behaviors of interest [35,36]. Schwaninger and Grosser illustrate how SD can be used to derive an initial theory of the dynamics driving a system's behavior over time [37]. SD modeling contributes to theory-building by providing a convention to make underlying assumptions explicit and test causal explanations through simulation. SD models, in both their quantitative and qualitative forms, give us tools to identify key variables of a complex system and diagram dynamic causal pathways that explain behaviors – positive or dysfunctional—over time [37]. In our case, the behavior of interest is adoption of clean energy technology in rural India. Qualitative SD models can facilitate knowledge capture of mental models and generate deeper understandings of process, structure, and strategy [38,39]. Using the diagramming conventions of SD, the project team developed a qualitative stock and flow diagram using Stella Architect (Version 1.5.2) software [40]. The model represents a set of assumptions, or initial theory, about the accumulations, delays, and feedback mechanisms driving diffusion and adoption of solar PV technology in rural Indian communities.

The strength in this approach lies in its ability to connect multiple sub-systems and make their complex feedback mechanisms explicit. One model can incorporate elements of rural market supply, financial mechanisms, social norms, and other such factors that have been identified as important but often previously treated in isolation. Without an exploration of the underlying structure, behavior of a system over time may seem counterintuitive [34,41]. The benefits of solar technology are clear and many of the individual barriers to implementation are understood but still widespread adoption is not evident. We developed a qualitative SD model to establish our emerging theory to explain this behavior. This is the first step in an iterative process which will be followed by validation through exploration of communities' mental models and confidence building through quantitative simulation.

Our paper presents a framework to understand sustained use of solar PV among the rural poor as emergent from an interaction of localization, affordability, and saturation of technology. The Localization, Affordability, and Saturation (LAS) framework is derived from the experience of the Million Solar Study Lamps Program, an off-grid solar PV intervention implemented in rural India between 2014 and 2016. The model is derived from the dissemination and implementation experience of this solar lamp program and qualitatively explores factors that drive solar lamp production, sale, use, and maintenance. Through this SD model we develop an initial theory of how feedback and system structures drive diffusion and adoption of solar PV technology.

2.3. The Million Solar Study Lamps Program

The Million Solar Study Lamps Program (MSP) was designed to address the lighting need of rural school students. The objective of MSP was to provide solar study lamps to one million rural students, in a fast and cost-effective way. The program was implemented simultaneously in four Indian states across 23 districts and 97 sub-districts with an emphasis on replicability. MSP successfully distributed and maintained one million solar study lamps in more than 10,900 villages across fours states [42]. Intended beneficiaries were from the lowest socio-economic class with low purchasing power and resided in areas where a market for distribution and sales of solar products was absent.

MSP trained 1409 people from local communities in the assembly, marketing, sales, and after-sales repair service of solar lamps. Non-governmental organizations (NGOs) were involved in the intervention sub-districts to increase outreach and manage activities including data management, monitoring, and quality assurance mechanisms. Using rural schools as the distribution base, solar lamps were distributed to students enrolled in grades five through twelve. MSP established 350 after-sales service centers in the intervention sub-districts to provide free repair service for a year, ensuring timely repairs and sustained use of the lamps by the beneficiaries.

3. Solar PV implementation dynamics: localization, affordability, and saturation

The system dynamics model we developed includes three subsystems. Fig. 1 presents a high-level causal diagram highlighting the interaction of three subsystems in MSP to drive adoption and sustained use of solar study lamps. Over time, *Localization* increases *Affordability,* and promotes *Saturation*. *Saturation* reinforces *Affordability* and further enables *Localization.*

Each subsystem is depicted using SD diagramming conventions. Stocks, depicted as squares, represent accumulations of attributes in the system and flows, depicted as pipes, represent the rate of change in a stock. Arrows represent causal connections. Arrows with a negative sign represent a negative causal connection where if the cause increases the effect decreases. Arrows with an addition sign represent a positive causal connection where if the cause increases the effect increases. The visual depictions represent an assumption about the underlying

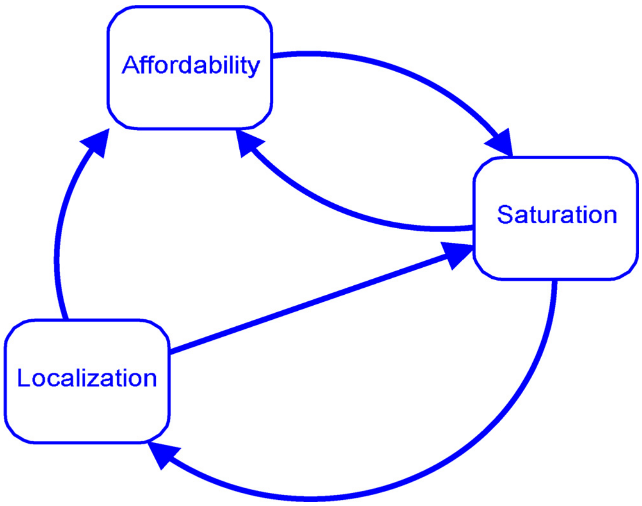

Fig. 1. High-level connections between model subsystems.

equations. While this is a qualitative model, we assume that stocks could be calculated as integrals, flows as derivatives, and other variables as constants or convertors for calculating interactions. The diagrams can therefore be interpreted in terms of accumulating levels of stocks, changing rates of flows, and variables interacting in causal connections forming feedback loops [41].

Fig. 2 depicts the *Localization* subsystem and how it interacts with *Affordability* and *Saturation.* Key stocks include *NGO Capacity for Solar* and *Local Skills*. NGO Capacity to mobilize communities and organize assembly and distribution of technology is relevant for variation in the stock of local skills over time. *Localization* dynamics include supply chain feedback processes related to lamps assembly, in stock for distribution, and lamps in use and not in use (depicted in the bottom half of Fig. 2). The feedback mechanisms between nongovernmental capacity, local skills, and supply chain systems drive the affordability and availability of solar lamps in communities. MSP identified NGOs in the different regions to train and employ people in local communities to establish a solar lamp assembly and distribution supply chain. *NGO Capacity for Solar* represents the capacity for supporting solar lamp assembly, distribution, and service support which is made possible with the injection of *Funding, Infrastructure, and Human Resources.* In the MSP, there were nine NGO partners. Seven partners took ownership of the intervention, reinforcing *Localization*, whereas two NGOs showed a lack of ownership, negatively influencing *Affordability* and *Saturation*. NGOs committed varying level of human resources to manage project implementation. As a result, when staffing was adequate and timely it led to well executed assembly, distribution, and a rise in demand for solar lamps in the community.

Whereas a delay in hiring by NGOs in other locations caused accumulated delays in solar lamp distribution and weak demand in those communities. Weak demand generation drives lamp sales down, reduces employment generation, the setup of after-sales service centers, and a lower uptake of solar lamps overall. In some cases, as projects achieved success, NGOs set aside additional resources that reinforced their *Capacity for Solar*. MSP coordinators sought to strengthen the capacity feedback loop by introducing management training to improve quality assurance, record maintenance, and overall operations management, which contributed to smooth supply chains. In this way, *Funding, Infrastructure, and Human Resources* of local NGOs and similar partner organizations enabled successful *Localization*.

NGO Capacity for Solar sets in motion *Local Employment* and *Skill Development* as the NGO employs and trains community members. Community members' ability to do these tasks is represented as a stock of *Local Skills* that initiate the flow of materials through the structure of feedbacks in the solar lamp supply chain. We found in MSP, as community members become more skilled, *Confidence in the Technology* also increases. *Local Employment* in the project raises *Awareness* of the solar lamps as well as *Average Household Income*. Local staff are able to build rapport and communicate with their fellow community members, increasing *Confidence* and creating *Awareness* about the lamp and its benefits. *Awareness* is also promoted directly through *Awareness*

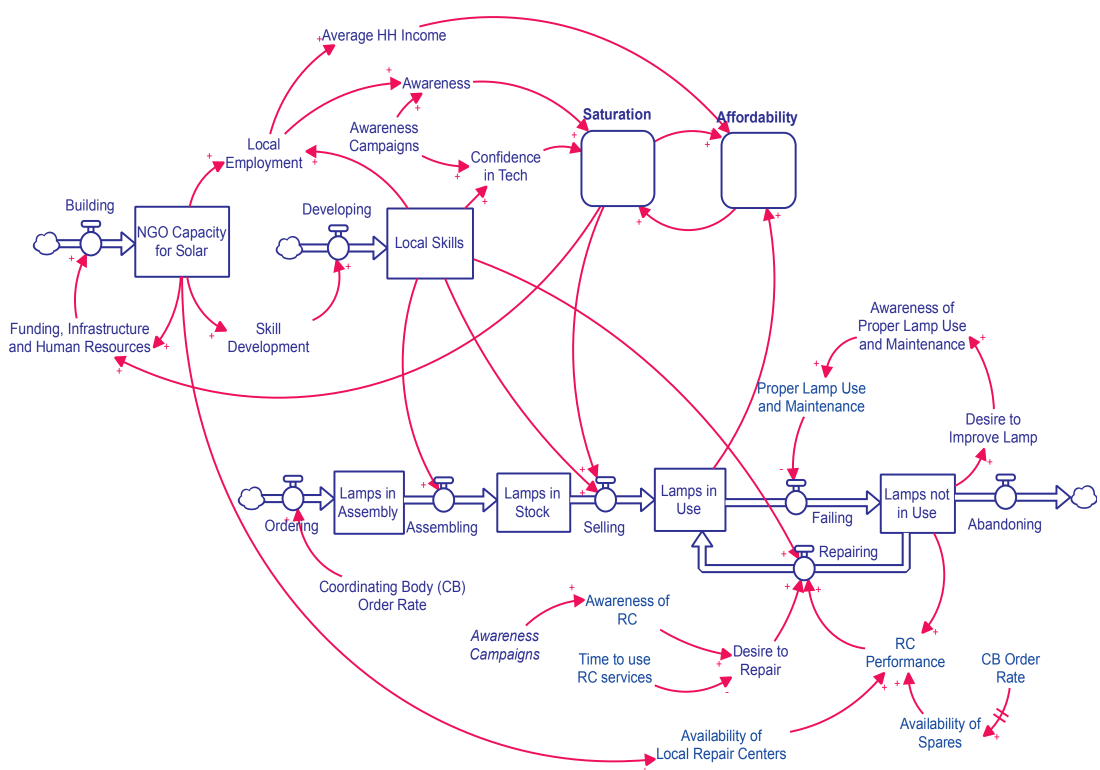

Fig. 2. Localization Subsystem.

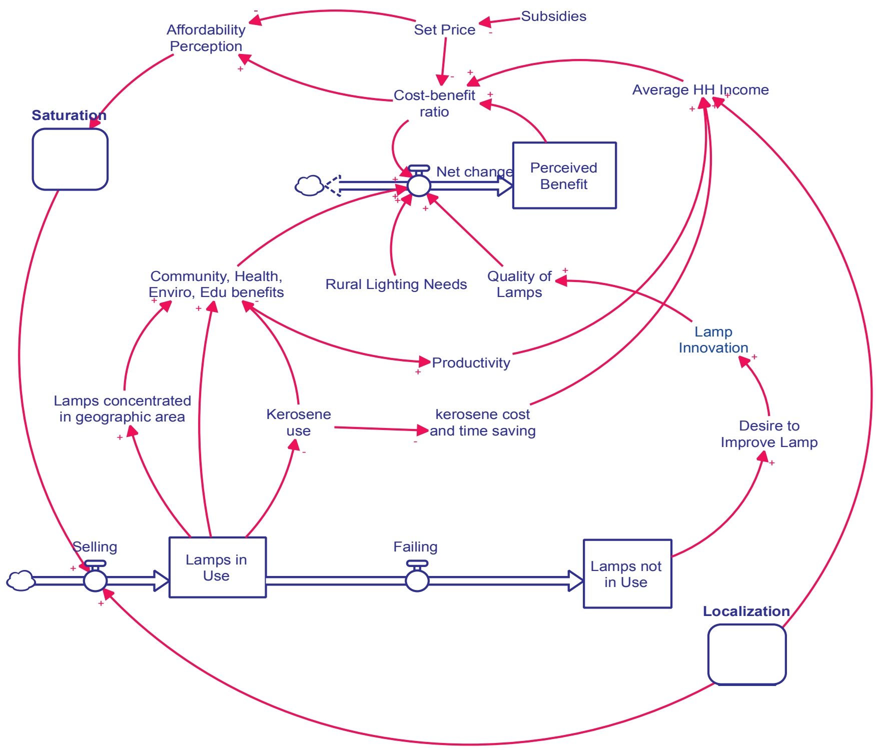

Fig. 3. Affordability Subsystem.

Campaigns led by project staff. All these factors in turn drive *Affordability* and *Saturation*. Enabling *Localization* is therefore a critical first bundle of processes for introducing renewable energy technologies. *Local Employment* and *Skill Development,* along with a community-based supply chain, contribute to the local economy and eventually create 'economies of scale' and reduce average long-term costs involved in the production, supply, advertising, management, and after-sales service of technology.

Fig. 3 shows the dynamics of *Affordability* and how they are connected to *Localization* and *Saturation.* Access to solar lamps in rural communities is only possible when the technology is affordable. Government *Subsidies* reduce the *Set Price* for beneficiaries by 76% to INR 120 (approximately 1.80 USD). *Affordability* in addition to *Rural Lighting Needs* and *Set Price* influence individuals' purchasing decisions. *Perceived Benefits* of solar lamps affect how people view the *Set Price*, resulting in a calculus of *Cost-Benefit ratio* (see Fig. 3). Users identified various benefits such as increased study hours for children in clean light, reduced exposure to pollution and reduced health or fire risks to children previously caused by kerosene lamps. *Kerosene Use* reduced as households transitioned from kerosene wick lamps to solar. Beneficiaries noted increased household productivity from a wide range of uses for the lamps, including their use while cooking, lighting at dinner, and performing household chores, irrigating farms, or selling goods in the grocery shop or marketplace after dark. Households also reported the versatility and use of solar lamps for evening social gatherings, village level meetings, emergencies, using an outdoor toilet, and as protection from wild animals at night. The versatility and range of uses are represented as *Community, Health, Environment, and Education Benefits* of solar lamps in Fig. 3. The model shows that these benefits accumulate, and are depicted as a stock of *Perceived Benefits*. As the stock of *Perceived Benefits* increases, individuals' *Affordability Perception* increases, leading to saturation or a dense coverage of a geography with solar lamps. Future efforts should further explore how dynamics of *Affordability* drive *Saturation* of solar technologies.

After-sales service of the solar lamps (bottom right of Fig. 2) is designed as integral to the *Localization* process to ensure solar lamps remain in use and contribute to driving their *Affordability* in these communities. In the MSP, the initial product cost included one year of after-sales service at a local repair center. Concerned about low after-sales service utilization, MSP held *Awareness Campaigns* so beneficiaries were aware of the services to maintain and continue using the lamps. Lamps in disrepair also motivate a *Desire to Improve Lamps* (Fig. 3), and drive *Awareness of Proper Lamp Use and Maintenance.* Solar lamp owners were instructed on *Proper Lamp Use and Maintenance*; charging the lamp regularly, keeping the solar panel dust free, and not playing with the lamp gooseneck. *Desire to Improve Lamps* drives *Lamp Innovation,* including changes to the lamp base and a design switch to make it dust and moisture resistant, resulting in a change in the *Quality of Lamps;* generating an important feedback loop in *Affordability* (Fig. 3).

Over time the structure of feedback processes in localization and affordability drive initial uptake, sustained adoption, and maintenance of solar lamps. With time, there is saturation or coverage of solar lamps; widespread and routine use of such technologies in a region. *Saturation* subsystem (Fig. 4) represents these dynamics in three key stocks of people: *Potential Adopters, Adopters,* and *Deadopters,* representing individuals who conceivably could become solar users, become adopters of a solar lamp, and others that have previously adopted become deadopters by abandoning solar technology. *Localization* and *Affordability* broadly affect the rate of *Adopting* solar lamp technology by enabling access and promoting benefits through a structure of feedbacks previously discussed. As *Adopters* encounter *Potential Adopters* they increase the rate of *Adopting* through the *Word of Mouth* effect reinforcing adoption. As the number of *Adopters* increases in a community, perceived benefits grow, which increases *Affordability* and further spurs adoption. *Adopters* also create a growing *Demand for Solar Lamps* and increase *Localization* in communities where NGOs set aside additional resources for project. This creates another feedback effect in generating more *Local Employment* and *Skill Development* which in turn raise *Average Household Incomes*, *Awareness*, and *Confidence in the Technology.* Eventually these feedback mechanisms affect the rate of *Adopting* solar lamps. In the absence of repair centers, people abandon the lamp when it fails and eventually *deadopt* the technology entirely.

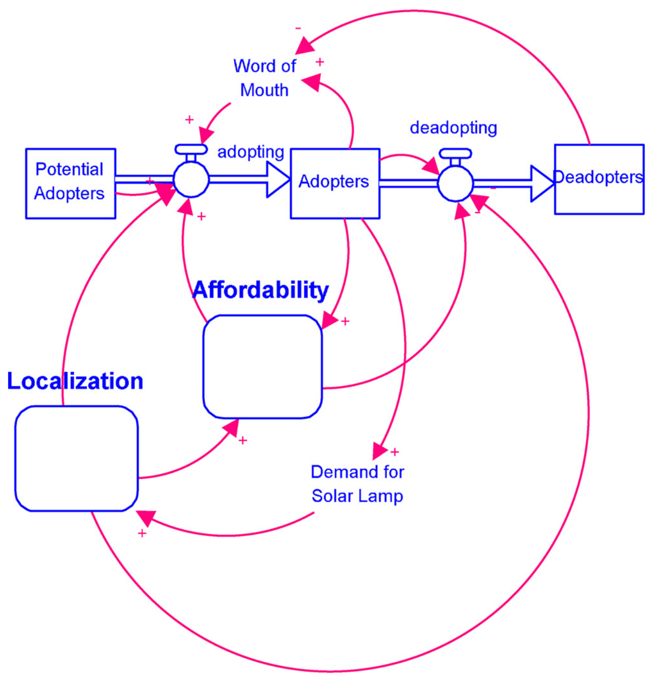

Fig. 4. Saturation Subsystem.

In this structure, it is likely that the behavior of *deadopters* will adversely influence adoption rate as dissatisfaction with solar lamp technology is broadcast and signaled to other community users. Recognizing this dynamic, MSP designed local repair centers to keep solar lamps in use and awareness campaigns to continuously promote solar lamp technology.

4. Conclusions and implications for solar and clean energy implementation

A system dynamics approach provides insights into the many causal loop mechanisms from the Million Solar Study Lamps Program and in the process develop a model of feedback mechanisms that drive adoption and sustained implementation of solar lamp technology in low resource communities. Insights from MSP and the LAS framework demonstrate the importance of *Localization* in the diffusion, adoption, and implementation of decentralized energy systems in poor rural communities. Establishing a local workforce and being attentive to supply chain issues help communities to leverage benefits from solar lamp production, distribution, and use of lamps.

Several insights from the dynamic model are important for understanding past, current solar interventions, and designing future clean energy projects. In general, the feedback between solar demand and the support capacity of local organizations is an important mechanism. For example, the Lighting a Billion Lives program has a single Solar Charging Station unit that consists of a fixed supply of 50 lanterns which does not include a feedback mechanism to respond to demand and could constrain the community from realizing the full benefits of solar [43]. Localization of solar or any other clean energy technology is possible only when local nongovernmental or community organizations have the resources and capacity to meet emerging demand. Demand is generated by localizing the solar market, including assembly and distribution, which increases confidence in the technology and makes the product affordable. Such localization relies on developing a stock of local skills to support the process. Again, using the Lighting a Billion Lives example the program is designed to promote local skill development. The LAS framework provides an initial theory of how this skill development potentially has a positive effect on confidence in technology, promoting adoption, as well as supporting the lamp's repair and maintenance therefore increasing sustained lamp use.

Another insight from the LAS framework is to understand the adoption and spread of solar technologies among a stock of potential adopters as opposed to those who only took up solar lamps. Potential adopters come into contact with those who have already adopted the solar lamp. The user's decision to purchase and maintain solar lamps is initially based on perceived benefits that are subject to others' positive or negative perceptions. There is a delay before users experience all the benefits of solar technology. The model demonstrates that this time delay, before users experience benefits, could also influence potential adopters who are trying to decide whether the solar lamp is beneficial and therefore worth adopting. This could also have implications for users who are deciding whether the solar lamp is worth maintaining. After-sales service to keep the lamps working is also important in driving maintenance of lamp use, keeping the lamps affordable, and supporting continued use of solar technology by users. After-sales service experience creates a feedback mechanism between user experience and lamp design establishing a path to innovation on lamp design and keeping users engaged with the technology. The LAS framework can be used to generate these kinds of insights for the implementation of other clean energy projects.

While the LAS framework is useful in establishing initial theory and corresponding insights, additional validation of the SD model is needed [37,41,44]. The current model reflects the perspective, or collective mental models, of MSP project staff. The model offers key theoretical insights but needs to be validated with communities, local assembly and distribution and repair and maintenance centers involved in the different sub-systems and incorporate their unique mental models. A Community Based System Dynamics (CBSD) approach emphasizing the importance of community participation in the modeling process to understand the different perspectives of these actors in the system is ideal to test our theoretical framework [41]. Community participation improves clarity of the problem and creates buy-in for the insights and recommendations that stem from the model [45]. We plan to conduct group model building with solar PV users and providers of the technology to understand diffusion and adoption from their perspective.

In addition to qualitative validation of different perspectives, the various subsystems and the feedback structure driving adoption and sustained use of solar lamps in this paper can be further tested quantitatively through simulation for accuracy and validity. We plan to test the casual connections depicted in the LAS framework and parameterize the model using data from the implementation of the next wave of seven million solar PV units that is now underway. Once a full quantitative simulation model is developed, simulation runs should be tested against historic project data, as well as data trends from other similar solar technologies, to see if the model replicates behavior. Sensitivity analysis, testing how responsive the model is to changes in parameter values, will also help us determine whether our initial dynamic theory is applicable to other situations or if further development is needed to create generic structure. A suite of confidence building exercises will continue in an iterative fashion to further refine and validate the model [44]. Local capacity, quality of the technology, perceptions, repair services, affordability, and awareness of solar energy technologies, need careful attention in subsequent solar lamp or off-grid solar projects. Other solar and clean energy projects in India and elsewhere can utilize this model to specify and understand the core feedback loops central to their outcomes.

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