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Perspectives

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