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Theory of Change for Off-Grid Solar Uptake in Emerging Economies – a Means to Identify Drivers and Barriers, and Develop Appropriate Interventions

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THEORY OF CHANGE FOR OFF-GRID SOLAR UPTAKE IN EMERGING ECONOMIES –

A Means to Identify Drivers and Barriers, and Develop Appropriate Interventions

by

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B.S. Arizona State University, 2010

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A Means to Identify Drivers and Barriers, and Develop Appropriate Interventions

written by Kyle M. Karber

has been approved for the Department of Mechanical Engineering

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Michael P. Hannigan, Ph.D.

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Date____________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

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Karber, Kyle M. (Ph.D., Mechanical Engineering)

Theory of Change for Off-Grid Solar Uptake in Emerging Economies –

A Means to Identify Drivers and Barriers, and Develop Appropriate Interventions

Thesis directed by Professor Michael P. Hannigan

Abstract

In Sub-Saharan Africa almost 600 million people currently live in the darkness of energy poverty, and millions more will be without energy access in 2030 due to population growth and slow grid expansion. Solar PV technology is a viable alternative to grid expansion, and off-grid solar products (<10W-1kW) are projected to make a significant contribution toward achieving the United Nations' goal of sustainable energy access for all by 2030. Off-grid solar products will save people money, supply more and brighter light, create opportunities to generate income, and have a positive impact on health, education, gender equality, the environment, and quality of life. While numerous stakeholders have made substantial efforts to grow this market, progress has been hindered by a limited understanding of the processes which underlie solar technology adoption in emerging economies. I aimed to reveal these processes by developing and applying a holistic theoretical framework that illuminates the off-grid solar technology adoption process.

I synthesized the relevant literature into an actionable theory of change that elucidates the fundamental mechanisms which drive solar adoption in Sub-Saharan Africa. I utilized this theory of change to integrate a broad array of data and model results originating from 324 surveys of current and potential solar users in Northern Tanzania. The theory of change allowed my colleagues and I to draw more concise and meaningful conclusions. We found that limited awareness of financial benefits was the main barrier preventing additional solar market growth in this area. The theory of change also provided guidance as I developed an intervention to address this barrier. I proposed an intervention, and rigorous evaluation thereof, which will raise awareness through first-hand experience with solar products, underscore the benefits through

automated text messages, and increase peer referrals through text-based incentives. This intervention could be implemented by the relevant stakeholders to potentially increase solar uptake, and contribute to achieving sustainable energy access for all by 2030 – the ultimate motivation behind developing and applying this off-grid solar theory of change.

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1 Introduction

Energy poverty is entangled with many other dimensions of poverty, from the businesses that stop being productive and the children that stop studying as soon as the sun goes down, to the errors that occur during nighttime emergency medical procedures veiled by kerosene's flickering orange glow and acrid smoke that causes eyes to well; from agriculture, to information and communication technology for development; from gross domestic product, to women's empowerment [1]. In an effort to tackle the interrelated issues which contribute to poverty, the 193 member states of the United Nations General Assembly approved the Sustainable Development Goals in 2015, with the aim to eradicate poverty, protect the environment, and bring prosperity to all. Sustainable Development Goal 7 is to "ensure access to affordable, reliable, sustainable and modern energy for all" (SE4ALL) [2].

Emerging economies in Asia, South America, and the Middle East are already on a trajectory to nearly achieve SE4ALL by 2030. This is not the case in Sub-Saharan Africa (SSA), where almost 600 million people currently live in the dark, and millions more will be without energy access[1] in 2030 due to population growth and slow grid expansion. Viable grid alternatives and expanded efforts are needed to alter this trajectory and put SSA on a path to achieve SE4ALL.

My efforts to increase electricity access in SSA began when I was an undergraduate student, working to develop a low-cost wind turbine design that could be constructed locally in Malawi. The design concept started out as a Savonius-type wind turbine that used a 55-gallon drum as a rotor, but I soon realized that its low-speed design was not well suited to making power. In search of a more appropriate design, I found an open-source plan for a handmade three-bladed wind turbine. I worked to adapt it to low-cost parts that I assumed would be available in country, utilizing junkyard car parts for some of the main components. When I traveled to Malawi and

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[1] In terms of the SDG, energy access refers to electrical and heat (cooking) energy. Though I do not focus on cooking, I continue to use the term "energy access" for continuity and to encompass electrical and light energy.

Kenya in 2010 I learned that these “junk” parts carried prices higher than that of the new components specified in the original design.

I had to refine my approach once again, but I had little opportunity to do so as graduation came and went, and the effort of a full-time job left little energy to put toward the project I had become so passionate about. This passion led me to CU Boulder, where I was fortunate to be able to further research and develop low-cost locally-produced wind turbines in graduate school. As I gained a better understanding of electrification issues in SSA, I believed that a pico-scale (~10W) wind turbine might better address the needs and budgets of individual households in developing communities. This technology could be cost competitive with existing pico-scale solar products, while creating more jobs in country.

In 2014, I traveled to Tanzania to assess the feasibility of the pico-turbine. I was taken aback by the number of people using crude locally-made kerosene wick lanterns as their primary source of light, even though I knew the statistics: in the absence of electricity about two thirds of people in SSA use kerosene as their primary source of light. Households can spend 10-25% of their income on kerosene for light, since kerosene is very expensive in relation to its dismal light output [3]. Beyond the expenses and dim light of kerosene, there are many other disadvantages: indoor air pollution that impairs lung function and increases the risk of tuberculosis, asthma, and possibly cancer [4,5]; safety risks due to poisonings, fire, and explosions [4,5]; and greenhouse gas and black carbon emissions that have a significant contribution to climate change [6]. As such, the WHO Guidelines for Indoor Air Quality discourage the use of kerosene [7].

Figure 1.1: Tanzanian woman with kerosene wick lantern made from a tin can.

Unsurprisingly, Tanzanians had nothing but disparagement for kerosene lanterns. So why are so many people using them? It is not necessarily the lack of alternatives, as I saw many retailers in the area selling solar lanterns for as little as $7; these would pay for themselves in kerosene savings in a matter of months. During interviews and conversations with people, essentially everyone was aware of solar technology, and most had overwhelmingly positive opinions. So, the question in my mind was no longer “why are people using kerosene?” Instead I wanted to know “why aren’t people using solar?!” Furthermore, if people are not using the available, affordable, well regarded solar options, why would they use my wind turbine – an unfamiliar technology for almost everyone that I talked to?

I went through four wind turbine iterations before realizing that solar technology was a more appropriate solution in the current time and given setting. This was a tough realization, but the underlying lesson was one of the more important of my graduate education. Another central realization was that the issues impeding energy access in SSA could not be addressed by technology alone. I had to identify these impediments; I had to find out what is preventing people from ditching their smoky, dangerous, dim kerosene lanterns for clean, cost-effective, bright solar lanterns (and other solar products).

Figure 1.2: Solar lanterns, some with phone charging capability (top), and 100W solar home system with lights, TV, radio, and portable lantern (bottom) [8–10].

These solar lanterns and phone chargers (<10W), solar home systems (10W-1kW), and solar microgrids (1kW-1MW) are projected to make the largest contribution to closing the gap between the status quo and energy access for all in SSA by 2030 [11]. My research focuses on the lanterns and phone chargers, often referred to as pico-solar, and solar home systems (SHS), collectively referred to as off-grid solar. At the consumer scale, these products save money, supply more and brighter light, provide opportunities for generating income, and have positive impacts on health, education, the environment, and quality of life [12]. An estimated 6 million pico-solar products, and 600,000 SHS were sold in 2016 in SSA. In order to achieve SE4ALL the market for solar products will have to grow considerably, but sales are on a downward trend, falling by 12% between the first half of 2016 and the first half of 2017 [13]. While considerable interest and effort is being applied to grow this market, there has been limited success. I believe this is because there is limited understanding of the processes underlying solar technology adoption in emerging economies.

Rogers' Diffusion of Innovations, first published in 1962, is the seminal work on technology adoption. This theoretical framework provides an understanding of the principles which govern how new technologies and ideas spread, and the rate at which they do so. It was originally developed to understand the diffusion of agricultural innovations in Iowa, but it has proven to be applicable to a wide range of innovations and countries [14].

Eder, Mutsaerts, and Sriwannawit apply Rogers' theory to the diffusion of microgrids and renewable energy, based on a case study in Uganda. They identify the main dimensions affecting users' perceptions and the diffusion process as technological, economic, and social [15]. Other frameworks have been applied to technology diffusion in developing communities. For example, Tigabu, Berkhout, and van Beukering used Technological Innovation System to better understand the diffusion of improved cookstoves and biogas technology in Rwanda and Kenya [16].

Hirmer and Cruickshank used a value chain framework to evaluate the sustainability of the pico-solar market. They identified the most important considerations at each stage in the value chain, and five means of improving the sustainability of pico-solar product implementation [17]. Ulsrud et al. used a cluster of theories related to the transition to sustainability through socio-technical change to better understand a village-level solar power system in Kenya. Through this, they developed a five-step analysis framework for village-scale power systems [18]. Girardeau adapted a framework on LPG scale-up to identify the enabling environment factors that influence solar uptake in low-income countries, in order to improve solar programs. The environmental factors were the financial context, market development, program implementation, and government regulations [19].

Other researchers have explored the factors that impact technology adoption but have not started with a specific framework in place. For example, Ahlborg and Hammar used a literature survey and interviews to identify drivers and barriers of rural electrification in Tanzania and Mozambique. The drivers and barriers identified were organized into the following categories: financial, social, technical system management, local management, technology diffusion, actor performance, and rural infrastructure [20]. Barry, Steyn, and Brent used eight case studies in Tanzania, Rwanda, and Malawi to identify factors critical to the renewable energy technology selection process. They uncover 13 factors that should be considered when selecting energy technology for use in Africa [21].

Other researchers have developed their own frameworks for understanding technology diffusion in emerging economies. Slaski and Thurber developed a framework for understanding the diffusion of improved cookstove technology, which focused on the end-user perspective. They found motivation, affordability, and level of engagement required to be the three dimensions of cookstove adoption from the adopter perspective [22]. A second paper by Hirmer and Cruickshank focused on the perspective of the end-user. They drew on psychology, sociology, and design literature to develop a user-value framework for community off-grid electrification projects [23].

The above literature gives useful insights into various aspects of the technology adoption process. However, taken piecewise, it does not provide a comprehensive understanding nor adequate guidance to tackle the issues that are restricting growth of the solar market. Most of this literature focuses on other technologies, such as cookstoves and biogas, or different scales, such as grid extension and microgrids. Additionally, none of these studies provide an all-inclusive perspective of the technology adoption process, with some focusing on business aspects, others focusing on the adopter perspective, and many completely neglecting the adopter perspective. Perhaps the biggest limitation in the existing literature is that it does not provide an actionable framework for identifying not only the underlying issues, but also the solutions to these issues. My dissertation addresses these shortcomings by developing and applying a holistic theoretical framework detailing the off-grid solar technology adoption process.

In Chapter 2 I synthesized the above papers and other relevant literature into a comprehensive theory of change (ToC) that elucidates the fundamental mechanisms which drive solar adoption in SSA. The aim was to create a holistic, practical, and actionable theoretical framework for understanding off-grid solar diffusion. This is a meaningful contribution to the field, because my ToC provides a foundational understanding of solar adoption, which can be built upon by relevant actors to grow the solar market toward achieving SE4ALL. For example, the ToC can help guide research that identifies the drivers and barriers to solar adoption, then help develop appropriate interventions that address the barriers, enhance the drivers, and ultimately increase solar adoption. Chapter 2 takes the form of a paper draft that may be submitted to *Renewable and Sustainable Energy Reviews* after further revision.

In Chapter 3 I applied the off-grid solar ToC developed in Chapter 2, in order to demonstrate its utility for guiding research and drawing conclusions. In this chapter I answer the following research questions:

1. what are the drivers and barriers of off-grid solar adoption in northern Tanzania?
2. does my off-grid solar ToC provide a useful framework for interpreting research results?

I began to answer these questions by collaborating with an in-country research partner to carry out 324 household surveys in the Arusha and Kilimanjaro regions of Tanzania. These surveys provided useful insight into the perspectives and characteristics of solar adopters and potential adopters – perspectives that help explicate the change process underlying solar adoption, but are underrepresented in the literature.

By analyzing select survey questions with a fixed-effects model, then using the ToC framework to interpret survey and model results, my colleagues and I were able to draw concise and meaningful conclusions from a broad array of qualitative and quantitative data. We ultimately found that lack of awareness of financial benefits and affordability challenges among the poorest of the poor were the main barriers restricting further solar market growth in this area. Attraction to solar products and wide product availability were the main drivers contributing to the existing level of market penetration. Beyond identifying these drivers and barriers, and demonstrating the utility of the ToC, this research provides a useful contribution to the field in the form of valuable insights into the perspectives of (potential) solar adopters. Chapter 3 takes the form of a paper draft that will be submitted to *Energy Research and Social Science*.

In Chapter 4 I applied the ToC to develop an intervention that can address the barriers identified in Chapter 3. The ToC was useful because it brought together a diverse set of literature containing a range of ideas and evidence for broadly addressing barriers, in order to create an "enabling environment" for solar adoption. By looking at the parts of the enabling environment that were relevant to the identified barriers, and thinking about them in terms of the local context, I was able to develop a viable approach for improving awareness and affordability. The ToC also identified the stakeholders who may be relevant to this intervention, so I was able to refine the intervention such that it could realistically be implemented by these stakeholders, to their benefit. Thus, I operationalized the intervention so that it could not only be rigorously evaluated, but also realistically implemented at scale.

This resulted in a feasible plan for an intervention to address awareness and attraction, and potentially increase solar uptake in an effective and efficient manner. The fourth and final chapter takes the form of a hypothetical funding proposal to implement and evaluate a pilot version of this intervention, and serves as the conclusion of this dissertation. It shows the path forward not only in terms of the next steps of this research, but the potential direction of my career. This proposal also contributes to the field by outlining an intervention that could be realistically implemented, and successfully contribute to increasing solar uptake toward achieving SE4ALL – the ultimate motivation behind this dissertation.

2 Theory of Change for the Diffusion of Off-Grid Solar Systems in Emerging Markets

Kyle M. Karber, Katherine L. Dickinson, S. Revi Sterling, Michael P. Hannigan

2.1 Introduction

Modern energy access is a critical component of improving quality of life and enhancing human development in the Global South. Energy consumption has been shown to increase economic growth in both the short and long term for low income countries [24], and electricity access is positively associated with human development, gender equality, education, poverty, and lower maternal mortality [25]. Unfortunately, an estimated 1.1 billion people cannot realize the benefits of electricity access, with almost 600 million of those without access residing in Sub-Saharan Africa [11].

Fortunately, the International Energy Agency (IEA) projects the total number of people without energy access will drop significantly by 2030, when accounting for current policies and stated policy intentions. In this business-as-usual (BAU) scenario, near universal access will be achieved in India, Southeast Asia, Latin America, and the Middle East. Meanwhile, much of Sub-Saharan Africa (SSA) will be left behind. In this region, the total number of people without energy access will remain largely unchanged between 2016 and 2030. While additional electricity generation, grid connections, and decentralized energy systems in SSA will increase electricity access from about 43% of the population in 2016 to 60% in 2030, the total number of people without access will increase slightly due to population growth. About 90% of those who will remain without electricity access will reside in rural areas of SSA [11].

The United Nations (UN) envisions a much different scenario: Sustainable Development Goal 7 (SDG7) is to *ensure access to affordable, reliable, sustainable, and modern energy for all*, by 2030. As such, the UN has launched the Sustainable Energy for All (SE4ALL) initiative to leverage partnerships, develop strategies, and provide support that will facilitate leaders, accelerate action, and track success toward this goal [26]. The IEA explored the SE4ALL scenario to better understand how an additional 600 million people in SSA could gain energy access by 2030, and what the implications would be. In this scenario, 72% of the additional people would gain access through mini-grid and off-grid energy systems, which will be primarily powered by solar photovoltaics (PV). However, the SE4ALL case would require total investment of $454 billion in SSA, which is more than quadruple the expected investment in the BAU case. Even in the BAU scenario, 45% of future investments in SSA will be in mini-grid and off-grid systems, with a majority of these decentralized systems being powered by solar PV [11].

Since the deployment and use of decentralized solar systems needs to increase significantly in SSA, especially in the SE4ALL case, it is important to understand the drivers and barriers to the dissemination of this technology. Solar PV will be a leading technology for future electricity access in SSA and other areas of the world, partly because the cost of solar modules is rapidly decreasing – dropping 80% between 2009 and 2015 – making the technology increasingly affordable [27]. Additionally, decentralized solar technology is already widely available, and its modular nature makes it suitable for a range of needs and price points [11]. Off-grid solar products can range from a pico-scale LED lanterns and phone chargers smaller than 10 watts to multi-kilowatt solar home systems (SHS), with a large range of sizes in between. Mini-grid or microgrid systems are on the kilowatt to megawatt scale and are large enough to provide energy access to households in a community, and power equipment for communal services, such as grain milling and water pumping [25,28].

This paper focuses on off-grid solar products, which we will primarily refer to simply as “solar” going forward. Part of the reason for focusing on off-grid rather than mini-grid is because off-grid solar currently makes up the largest portion of the market, and these smaller and more affordable systems will impact a larger number of people in the short term [27,29]. From the consumer perspective, these products save money relative to kerosene and other traditional light sources, provide more and brighter light, provide opportunities for generating income, and can have positive impacts on health, education, the environment, and quality of life [12].

Off-grid solar products are already providing basic energy access for millions of people in low and medium income communities, who would otherwise not have access to electricity. Businesses which reported sales to Lighting Global and the Global Off-Grid Lighting Association (GOGLA) have sold more than 30 million solar lighting products worldwide since 2010, providing improved energy access for almost 100 million people. These sales numbers only account for businesses associated with and reporting to these organizations, and they do not account for SHSs which are sold piecewise, rather than as a bundled kit; thus, the actual solar product sales numbers are significantly higher [30].

Although global sales of off-grid solar products increased 97% between 2012 and 2014 and 9% between 2014 and 2016, there was a 15% decrease in sales of these products in 2017 [13]. In order to reverse this trend, surpass population growth, and achieve the Sustainable Development Goal of universal access to modern energy services by 2030, the off-grid solar market will need to expand considerably. Therefore, it is important to understand the mechanisms by which solar dissemination can be broadened and accelerated in low and medium-income communities, especially in Sub-Saharan Africa.

The overarching objective of this research is to convey an understanding of the fundamental drivers and barriers of off-grid solar adoption, and to help elucidate actions that can increase the uptake of solar products in SSA and other emerging economies. To achieve this goal, we examined literature relating to solar adoption from a range of perspectives, and synthesized it into a comprehensive theory of change. The secondary objective of this paper is to familiarize more people with the process of developing a theory of change (ToC). A systematic review found that there is no consensus on the definition of ToC, but it is “commonly understood as an articulation of how and why a given intervention will lead to specific change” [31]. Through the process of developing a ToC, the change agent (e.g. organization, government, etc.) acquires a better understanding of how their activities contribute to achieving a larger goal, while accounting for contextual realities (political, social, etc.) [32,33].

The insight gained through the process of creating a ToC helps with planning effective interventions, and developing monitoring and evaluation programs. The resulting evidence-based theory also serves as a tool for communicating the change process in an understandable and credible manner. As such, it is advocated, employed, or required by many development agencies (e.g. USAID, DFID), prominent non-governmental organizations (e.g. Annie E. Casey Foundation, Bill and Melinda Gates Foundation), and funding agencies (e.g. World Bank, International Initiative for Impact Evaluation) around the world [34–36]. Our off-grid solar ToC is a relatively unique application of ToC, in that these theories are most often created for specific projects or funding proposals, and are not usually published in the academic literature. However, ToC is broadly applicable and these theories are being increasingly used and published in a variety of fields, including education, health, and environmental research (e.g. [37–40]).

2.2 Methods

2.2.1 Theory of Change

ToC is a tool or methodology that uses a process of critical evaluation and backward mapping to identify and communicate the conditions and actions that can lead to a desired outcome, thereby resulting in a logical, practical, and actionable theoretical framework detailing the mechanisms of change. When a change agent uses ToC as a planning tool, they should not start with a specific intervention (i.e. program, activity, initiative, action) in mind. Instead, they start by defining the desired goal, then work backwards to identify the necessary contextual conditions (e.g. social, political, environmental), and the various change pathways which may enable them to achieve their goal. Once the change pathways are identified, the change agent can evaluate the different change pathways and develop interventions for achieving their goal [41]. By critically evaluating the landscape in which their goal is trying to be achieved, without procedural restrictions or preconceived interventions, the change agent gains a more unbiased and holistic understanding of the change pathways and their role in achieving the end goal.

The change agent's goal can often be broken down into the outcome and impacts, where the outcome is more directly related to the change agent's intervention, and the impacts are the overall result of the outcome. Depending on the purpose of the ToC and the objective of the change agent, they may want to start with the outcome (e.g. increase off-grid electrification), or start with the impact (e.g. improve education and health outcomes) and work backward from there. We started with the outcome of increased off-grid solar use, for the reasons given in the introduction, then we used the literature to identify/confirm the impacts of solar in Section 3. It is important to note that solar technology is not the only way of achieving the outcome of increased off-grid energy access, and increased energy access may not be the best way of achieving certain economic, health, or other impacts.

Change agents should draw on existing evidence to support the plausibility of their theory, including academic literature, available grey literature, program evaluation results, stakeholder and local knowledge, and results from pilot programs [31]. Change agents should also identify the indicators and evaluation methods they will use to assess the effectiveness of their intervention [41]. It is also critical that they subject their ToC to ongoing critical reflection; their theory should be continually revised as new evidence from ongoing program evaluation and other sources is considered, and as the political, economic, and social contexts change [42].

Besides the basic approach and core principals outlined above, the process of creating a ToC is broadly defined, and these theories can serve a number of different purposes and focus on different perspectives. The four main purposes for developing a ToC are strategic planning, monitoring and evaluation, communication, and learning; a single ToC can serve one or more of these purposes. The different perspectives or levels of analysis for the ToC include the project, organization, sector, or country level [31]. The flexible nature of developing a ToC allows its content and the presentation thereof to be tailored to a multitude of topics and applications.

The solar adoption ToC detailed below focuses on the sectoral level, i.e. the off-grid solar sector, and its purpose is learning, planning, and communicating. Through the process of creating the ToC we learned a great deal about the state of the off-grid solar market in Sub-Saharan Africa, which helped identify change pathways that can potentially expand the market. By explicitly highlighting these change pathways, the ToC provides a basis for planning interventions to increase the uptake of off-grid solar. The solar ToC also serves to communicate this information to a wider audience, including change agents who can use it as the basis for a ToC tailored to their specific organization, goals, and context. The breadth of this sectoral ToC also helps to define and communicate the roles of various actors.

2.2.2 Literature Review

Our ToC was developed using relevant academic and grey literature on the topic of off-grid solar technology adoption in SSA. This literature alone was not adequate to develop a complete ToC for solar adoption, so we included tangentially related studies, such as those on cookstove adoption in developing communities or community-scale microgrid electrification. We focused on literature pertaining to Sub-Saharan Africa due to the increased need in this region, but evidence from other regions was included where relevant. We focused on more recent literature as the off-grid solar market is continually evolving.

We did not use a formal search methodology, but our literature search was primarily conducted through Science Direct and Google Scholar using a variety of relevant search terms including different combinations of synonyms, such as [solar OR photovoltaic OR energy OR electricity] AND [“developing countries” OR Africa OR “emerging markets”]. The snowball method was also used, whereby the most relevant and useful papers were used to find additional relevant sources. Sources were selected for detailed review based on the perceived relevance after reading the abstract or skimming the document. Initially, more than 100 documents were saved for further review, 27 of these were selected for detailed review and included in this paper. These 27 sources helped identify about 50 additional relevant sources which are included in this paper.

In order to achieve the outcome of increased off-grid solar energy access, we needed to start with the perspective of the potential adopter/customer, as they ultimately drive the adoption process. Thus, we started developing our ToC by identifying the conditions that need to be met for the adopter to purchase a solar product, i.e. the “adoption conditions”. This aspect of the ToC was framed by the “the Four A’s”: awareness, attraction (acceptability), affordability, and availability, adapted from [43], because these categories represent the adopter’s perspective at a fundamental level.

With an initial framework in place, we began reviewing the publications perceived to be the most relevant—those that applied or developed theories, frameworks, or basic concepts for understanding energy technology adoption in emerging economies [14–17,19–23]. The lead author used a qualitative data analysis software, MAXQDA, to organize the review process. As I read through papers, I used the software to highlight relevant passages and assign those passages a code, such as one of the 4 A’s. As I reviewed more sources and identified more relevant passages, I created new codes when existing codes did not represent the content of a passage. For example, I identified and coded relevant actors, contextual factors, and dimensions within the 4 A’s. Through the process of reviewing literature, I found the 4 A’s adequately encompassed all adopter level conditions that were identified and coded, so I did not change this initial aspect of the ToC framework.

Besides starting with the 4 A’s, the organization of the ToC arose from the factors in the literature that I identified to be part of the change process for solar adoption. After reviewing approximately 27 relevant sources, I created an initial ToC outline from the codes identified therein. This initial ToC helped identify missing and underdeveloped topics, which guided the literature search going forward. As I found more factors influencing the 4 A’s, but that were external to the adopter perspective, I organized these external factors into the “enabling environment,” which directly relate to the adoption conditions, and represent intermediate conditions that need to be considered along various change pathways. As I reviewed additional literature and identified additional codes, I continued to reorganize the ToC as necessary so that it captured new information, was more intuitive, had better logical flow, and better reflected the change process. The resulting organization can be seen in the ToC diagram in Figure 2.1.

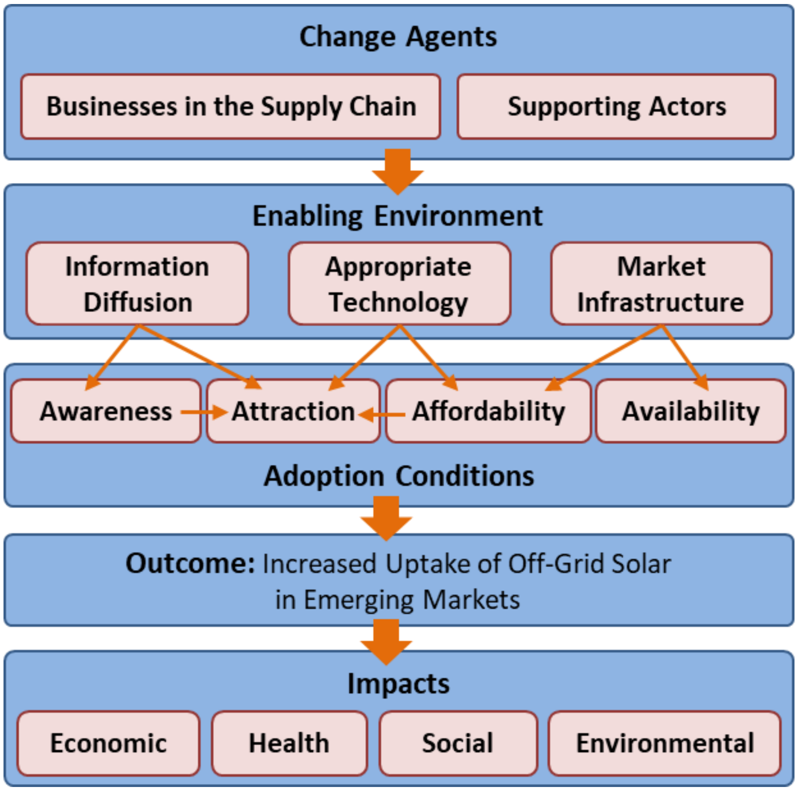


Figure 2.1: Off-grid solar theory of change diagram

2.3 Identifying Impacts of Off-Grid Solar

To begin the ToC we started by identifying the likely impacts of increased solar adoption, in order to verify that we are pursuing a worthwhile outcome. The most apparent impact of solar is additional lighting hours from a brighter higher-quality light source relative to kerosene and other traditional sources [12,29,44–47]. Beyond this, solar technology has economic, health, social, and environmental impacts, which are outlined in Figure 2.2.

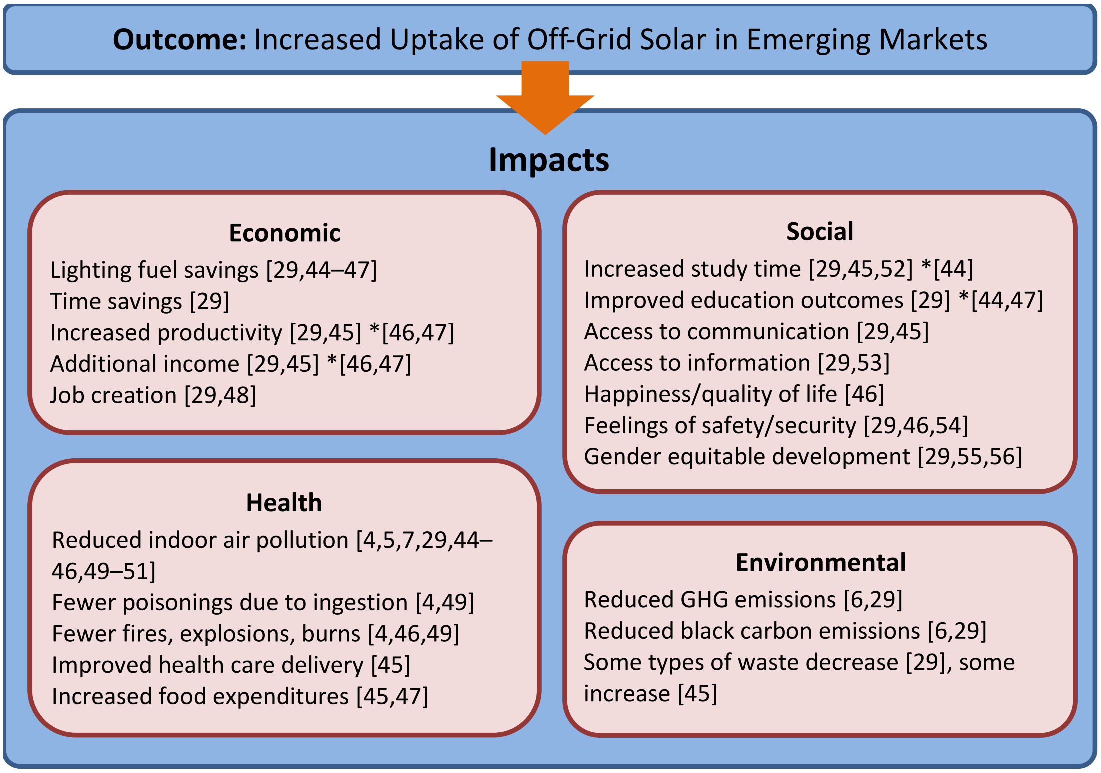


Figure 2.2: The economic, social, health, and environmental impacts of off-grid solar. Note: citations following an asterisk indicate findings which dispute the impact.

2.4 Adoption Conditions

The adoption conditions are the four fundamental conditions that must be fulfilled in order for consumers to purchase and use solar products. Adopters need to know about solar products, have a desire for them, find them economically feasible, and be able to purchase them locally; they must have *awareness* and *attraction* for the product, which must be *affordable* and *available* [43]. The Four A’s are analogous to the 4 P’s of marketing (product, promotion, price, and place) [48], but from the perspective of potential adopters in emerging economies, rather than the business or marketing perspective.

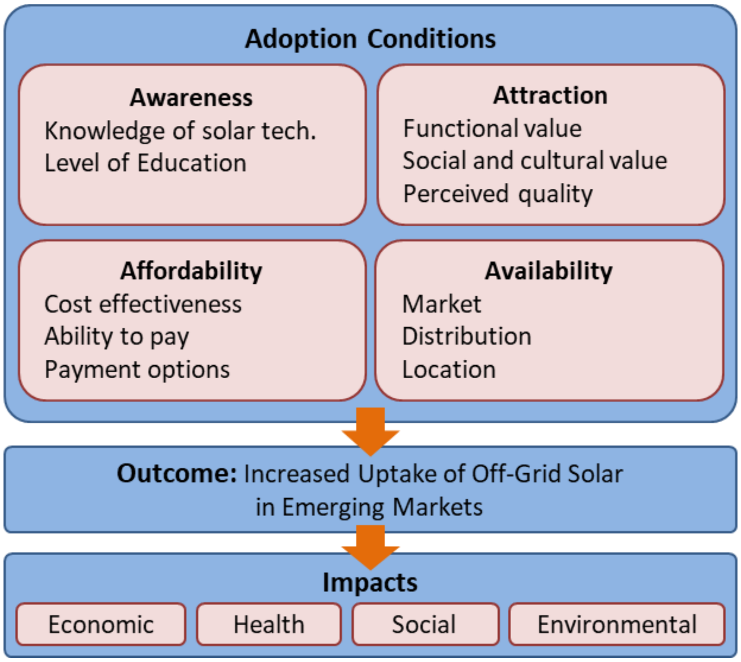


Figure 2.3: Theory of change diagram highlighting adoption conditions

2.4.1 Awareness

Awareness is an undeniable prerequisite to the diffusion of solar technology in developing communities [21,49–51]. In general, before awareness reaches 20 to 30 percent of a population there is very little adoption, but increased in awareness beyond this leads to increased adoption [14]. The two main dimensions of awareness are knowledge of solar technology and its benefits, and the level of education of the adopter.

Using the literature, focus groups, and interviews of experts who have experience with pico-solar, Hirmer and Cruickshank found that one of the key elements of sustainable product development for rural electrification is ensuring that end-users are aware of a product's existence and its benefits. However, they found a large disconnect between how critical this awareness is and the extent to which it is addressed by practitioners. Further, they expressed the importance of raising awareness and understanding of a product's benefits in transitioning to a technology "pull" by rural customers for pico-solar products. One of the experts interviewed said many end-users do not realize they need the product, and the authors reason this was due to low levels of pico-solar exposure. The authors concluded that the relative importance of this issue and the deficiency in addressing it are indicative of a major market failure [17].

Other researchers have noted the deficit of knowledge of off-grid solar products in SSA [15,44]. Based on the literature and in-depth interviews with stakeholders, Ondraczek concluded that lower awareness of solar products in Tanzania has led to lower uptake of the technology when compared to Kenya [50]. Amankwah-Amoah et al. found evidence in the literature that suggests people resist adopting this new technology due to a lack of information about the technology and its functionality [52].

When researching knowledge and adoption of SHS in Nicaragua, Rebane and Barham found that knowledge of solar technology was most strongly predicted by the presence of other installed SHS [53]. They also found that having learned about SHS from an NGO or business was a positive determinant of SHS adoption. When performing an econometric analysis on data from the Kenya Integrated Household Budget Survey of 2005/06, Lay, Ondraczek, and Stoever found that the more prevalent SHS were in the district, the greater the likelihood that another individual would adopt the technology [54]. They recognize that number of factors could have contributed to this outcome, including the importance of local knowledge of SHSs when a user is deciding to adopt.

These findings illustrate the importance of knowledge about solar technology in increasing the adoption of these technologies. However, raising awareness alone is not necessarily sufficient to increase adoption of solar technology. A household survey in rural Bangladesh showed that 87% of solar non-users were aware of the technology [55]. Furthermore, even if awareness of the relative advantages of electricity access is high, this general awareness does not necessarily translate to solar electricity [15].

One of the possible contributing factors to a lack of awareness about solar products and their benefits is the education level of potential users, which can be a barrier to technology adoption in general [21,50]. Lay, Ondraczek, and Stoever found that a higher education level was associated with an increased probability of using modern cooking and lighting technologies [54]. In Tanzania, Ikwaba found that the majority of SHS users completed secondary school education, and almost one-third had a university degree; none of the non-users had a university degree, and the majority had only completed primary school [56]. Education level was not only associated with the use of solar technology, but also the willingness to pay for that technology [57].

A possible reason for the link between education and solar use is that those with higher levels of education are better able to acquire and process new information [58]. This is reinforced by the observation that earlier adopters of technology tend to have more education and are more likely to be literate [14]. Another possibility is that education level affects adoption indirectly, by affecting income level or other related factors. Alternatively, higher education may facilitate gathering knowledge on the new technology, thereby leading to increased adoption. However, Smith and Urpelainen found no evidence that education affects the adoption of solar technology in Tanzania [51]. Therefore, it is unclear what role the level of education plays in adoption, if any.

2.4.2 Attraction

Beyond awareness, potential adopters must find these products attractive, thereby creating a demand for them. Currently, demand is not coming from the adopter side (market pull), but by businesses who are driving demand (technology push) [17]. For the market to grow and be successful, potential adopters must be motivated to purchase solar technology [17,51]. Though the demand for solar products may be lacking, the desire for electricity is evident [20]. Increasing demand for electricity may be driven in part by the rapid diffusion of mobile phone technology [54]. The demand for electricity needs to be more effectively translated into a demand for solar solutions, and a key part of creating that demand is increasing the attractiveness and perceived value of these products.

Demand for solar ultimately begins and ends with the adopter, who must see the value in these products [21,22]. Users' needs and desires must be taken into account when designing solar technology, in order to maximize their attraction to the product [59]. Through an extensive literature review, Hirmer and Cruickshank adapted existing user-value theories to create a user-value framework for rural electrification, which has been adapted to the structure of our ToC [23]. Certain aspects of the framework have been combined for simplicity and brevity: functional, epistemic, and emotional value are combined into a dimension called "functional and personal value," and social and cultural value have also been combined into a single dimension. Other aspects of their user-value framework were relevant to other A's, so they are discussed further in the applicable sections.

Functional Value

Value is user-subjective rather than objectively established, is inherent in the use of the products, and is weighed against what the user gives up to obtain the product [23]. Rogers refers to the trade-off of solar technology over competing or traditional options as "relative advantage" [14]. The relative advantages of solar need to be obvious to the adopter, and these advantages are often measured in financial benefits [15]. In economic terms, this would be the "net gain to the agent from adoption, inclusive of all costs of using the new technology" [58]. The economic aspects of functional value are explored further in the *affordability* section, but there are many non-economic factors that affect perceived value.

The non-economic aspects of functional value include the product's performance and personal compatibility [23]. The perceived compatibility of a new technology positively affects the rate of adoption [14]. A very important aspect of the performance and compatibility of off-grid solar products is their brightness [17,60,61]. Another desirable feature that would enhance compatibility is the ability to power a TV [50]. Other desirable features include reliability, adequate run-time, and mobile phone charging features [61,62]. To further enhance compatibility, the new technology should not be overly complex, but intuitive and easy to use with little instruction [14,23,63].

Other non-economic aspects of functional value include the product's convenience and service. Convenience includes time saved, such as avoiding time spent going to the market to buy kerosene or charge a cell phone. It also includes the flexibility to meet variable and increasing energy demand. Service includes support, training, and maintenance [23].

Personal value includes satisfying a desire for knowledge, provoking curiosity, and providing novelty and emotional value [23]. Not only is knowledge gained about the technology through its purchase and use, but opportunities to acquire more knowledge are increased due to additional light. In Kenya, there is a desire for a light switch and permanent bulb that are similar to those of a grid electrified house, because of the emotional value associated with a western lifestyle [23].

Issues which can negatively affect user-value for solar products must also be taken into consideration. Households may place a higher value on grid electricity, thus their willingness to pay for solar products is lower [57,64]. Similarly, some see grid power as more effective at charging battery-powered lamps, which may be partly due to the need to charge the solar lamp daily, rather than only when necessary with grid charging. Functional value may decrease when accounting for time and effort spent on managing the charging process and mitigating concerns of theft, where necessary [60]. However, in some contexts the perceived reliability of SHSs makes them more attractive than a grid connection [54]. Other issues arise when SHSs are not installed properly or incorrect information is given regarding system performance, which results in disappointed consumers whose expectations of system value were not met [61].

Social and Cultural Value

Societal norms, cultural values, and other social structures can influence an individual’s perception of a new technology. It is possible that tradition can be a barrier, and the “day-to-day culture” in rural areas can lead to disinterest in new technology [15,23,56]. If a population is skeptical of a new technology and reluctant to try it, the adoption process is hindered [50]. Furthermore, religion can be a deciding factor in purchasing decisions, and spirituality can lead to fear of unknown technologies [23,65]. However, this disinclination toward new technology is either not universal, or can be overcome, as evidenced by the rapid diffusion of cell phones in Sub-Saharan Africa and the popularity of television and radio, even in rural areas [50].

The attractiveness of solar or other new technologies is influenced by how these products fit into the local value system. Adoption can be impeded if the technology is incompatible with the values of the target market [15]. The perspective of the local society on new technology can be a major impediment of adoption [66]. Conversely, the local perspective can facilitate adoption, as is the case with more open and tolerant villages in Sri Lanka [65]. It is critical that any interventions aiming to diffuse solar technology to a population get local buy-in and acceptance [23]. It is also important to remember that business strategies must be adapted to the local context, since the social dynamics will vary greatly from location to location, even within the same country [15].

Solar products can be seen as a status symbol, which can further elevate the perceived value of these products. Pode states that the growth in the SHS market in Bangladesh is attributable, in part, to the desire to improve lifestyle [67]. In Kenya there is a desire for a more Western lifestyle, with which electrification is associated [23]. In South Africa, increased social status is one of the benefits associated with electrification in rural areas [68]. In fact, early adopters of solar products were driven in part by their desire to distinguish themselves from their peers [14,23]. Thus, when looking at the relative advantage of a new innovation, the associated prestige influences an individual’s perception of the innovation.

Though it may seem advantageous to promote solar products as a status symbol, this could also lead to conflict. Eder, Mutsaerts, and Sriwannawit observed discord between those who could afford a connection to a rural microgrid, and those who could not afford it in rural Uganda. The more affluent households used electrification as a status symbol, which increased the social divide in the community [15]. In other instances jealousy over SHSs has led to vandalism and theft [19].

The environmental sustainability of a technology can influence its perceived value as well. There were positive attitudes toward a biomass-based rural electrification scheme in Uganda because the villagers believed it was better for the environment [15]. Growth in the SHS market in Bangladesh can be partly attributed to the reduction in indoor air pollution resulting from reducing or eliminating the use of kerosene for light [67]. However, environmental factors are not always influential on purchasing decisions [17]. As with most things in international development, it depends on the local context, as attitudes toward the environment are likely to be highly variable from place to place.

Perceived Quality

Another element influencing the attractiveness of solar technology is the perceived quality of these products. Quality, service, and sufficiency are identified as the dimensions of reliability, which is an important parameter that influence a potential customer’s value judgement [62]. Inadequate or inaccurate information about the reliability of a new product is a market imperfection that inhibits adoption [49]. Inadequate information on quality is perpetuated by the over the counter nature of solar product purchases, which limit the ability of customers to assess reliability before purchase [69].

Low quality solar products are widely available on the market in developing communities [17,49,56]. Lighting Global created a product-testing and certification program for off-grid lighting products; of the 110 products submitted in 2014, only 45 met the minimum standards for quality [61]. Product submission was voluntary, so this already meager 41% pass rate does not include the multitude of low-quality products that were not subject to testing. Additionally, the real world failure rate is likely to be higher than those demonstrated in lab testing conditions [15,44]. In an RCT which deployed almost 700 Lighting Global quality-certified solar lanterns, around 10% were broken after 7 months [47].

Mills et al. took an in-depth look at lighting product quality issues in Kenya, and their potential consequences. They found that most low-cost LED flashlights have a lifespan of just a few months, and they were concerned that low-quality LED flashlights could create negative perceptions of solar lighting products, which also use LEDs; users of LED flashlights might conclude that all LED products are low-quality, including solar LED lamps, leading to "market spoiling" for these products. This market spoiling issue is an instance of information failure, since consumers are aware that there are low-quality products on the market, but they cannot differentiate between high and low-quality off-grid lighting products [61].

Mills et al. found statistically significant evidence of market spoiling occurring at the vendor level. These vendors were offered the business opportunity to buy a high quality solar powered LED lighting product for resale. 11 of the 12 vendors unfamiliar with LEDs chose to buy the solar LED lighting system, while 8 of the 11 vendors who had prior experience with low-quality LED products declined to buy [61].

Market spoiling and information failure lead to a number of negative outcomes: some customers will experience losses due to premature failure of equipment; some potential customers will decline to purchase products which could be beneficial to them, as a result of negative perceptions of quality; there is a lower perceived value and therefore a lower willingness to pay for affected products; there is the potential for the market for solar products to be devastated in the early stages of adoption [61].

Other researchers reinforce the danger of market spoiling (e.g. [17]). With regard to Rogers' diffusion of innovation theory, there can be a "chasm" between the early adopters and the early majority: poor quality products cause early adopters to communicate negative opinions to the early majority, thereby decreasing sales, deterring adoption, and causing a disruption in the diffusion process [15]. Such an issue can prevent the solar market from developing.

The market spoiling issue may be partly attributable to high-quality products having limited market share due to their higher price relative to low-quality products. Consumers tend to favor lower-cost options, which tend to be lower quality [17]. These low-cost low-quality products fail to perform to the customers' expectations, which leads to a breakdown of the bourgeoning market, as described above. This issue is further compounded by low-quality imitations of high-quality products, which are readily available on the market [67]. These hard to identify products cause further information failure when low-quality products are mistaken for what was supposed to be a high-quality product.

Users may desire a warranty on their solar products, to reassure them that the products are high quality [61]. However, there is some evidence that consumers put little faith in a warranty, as it may be difficult for the consumer to act on the warranty, or it may not be honored due to the solvency and reliability of companies in a startup environment [25,70]. Though a warranty may not be the best solution, there needs to be some means of boosting consumer confidence in off-grid solar product quality, in order to increase consumer's attraction to these products.

2.4.3 Affordability

Affordability is one of the primary drivers or barriers of the diffusion of off-grid solar technology in emerging markets [50,66]. This importance is not only reflected by the focus on this topic in much of the literature, but also by the concentration of donor funding and policies [71]. However, in 2013 Bhattacharyya stated that "renewable energies are already cost-competitive in many parts of Sub-Saharan Africa," and that is even more true in 2017 as the cost of solar PV cells continue to drop [64,72]. Still, uptake is limited by dimensions of affordability beyond the upfront cost, including cost-effectiveness, ability to pay, payment flexibility, and the availability of financing and subsidies [23,50,67].

Cost Effectiveness

Kerosene expenditures for lighting can account for 6% to 12% of household income in emerging markets [45]. Thus, solar lighting products can provide substantial savings on kerosene. Grimm et al. carried out an RCT in Rwanda, which showed solar lamp users consumed 128% more light per day (lumen hours) while their kerosene expenditures were 70% lower [44]. Similarly, Adkins et al. found that lighting expenditures dropped by 86% the week following purchase of a solar LED lantern, while lighting hours increased by 63% [63].

In Kenya, Malawi, Tanzania, and other countries, households pay the connection costs when they are initially connected to the grid, and these costs can be comparable to the price of a solar home system. Though the upfront cost can be comparable, those with grid connections will continue to pay monthly based on their electricity usage, unlike SHS users [54]. Thus, when faced with similar upfront costs for a solar system or a grid connection, the solar system will be more cost effective.

It should be mentioned that the amortized cost per unit energy for SHS is higher than that of a grid connection (not accounting for potential grid connection costs), but is much lower than that of kerosene [25]. This cost premium compared to the grid is irrelevant in rural areas where grid power is not an option. A diesel generator powered microgrid co-op in Tanzania was found to have a cost of electricity 15 times higher than the cost of grid electricity in a nearby town. This did not negatively affect the co-op, which saw an increasing number of subscribers due to the lack of alternatives as of 2002 [64]. This implies that the opportunity cost of forgoing electricity is significantly greater than the cost of grid electricity, thus making solar power cost effective where a grid connection is not an option or is unreliable.

It is unclear if there is a good understanding of the financial benefits among potential solar users, which can include: direct savings on kerosene, phone charging, and batteries; possible indirect savings on healthcare due to reduced indoor kerosene pollution; and increased opportunities for income generation – either through increased work hours due to light, or productive uses of the energy generated [25]. Schäfer, Kebir, and Neumann believe that future implementation strategies should focus on financially productive uses of off-grid energy, which would further enhance cost effectiveness of the technology [59].

Ability to Pay

Even if a consumer finds solar products to be cost effective, financial constraints may prevent their purchase. A number of researchers have found income to be a factor for adoption of improved cooking fuel or modern energy services such as solar products [15,52,55,63,73]. Lay, Ondraczek, and Stoever found evidence to support the energy ladder hypothesis: a household's energy or fuel choice depends critically on the level of income of the household, and as income rises the household will move up from traditional fuels to transitional and modern fuel and energy options [54]. For those living in poverty, it would be difficult to make the step from kerosene and other traditional sources to a solar product, regardless of how cost effective it would be [20]. At the same time, the increasing purchasing power of the rural middle class has contributed significantly to the expansion of the solar market in Kenya [50]. However, a study that used a nationally representative survey in Tanzania found income only had a small effect on the likelihood of solar ownership, deviating slightly from the studies cited above [51].

A number of researchers cite the upfront cost of solar systems as one of the main barriers to their adoption [15,23,66], which leads to slower overall diffusion of this technology [52]. Fortunately, the downward trend in solar pricing is making these products more financially accessible [54,72]. Despite the decreasing costs of solar products, many consumers still do not have the cash to pay for these products upfront [67,73], and most transactions are cash over-the-counter [64]. When cash and credit constrained individuals are accustomed to smaller daily purchases, preferences for today's consumption override the relatively high upfront costs of solar products [17,25]. These individuals are also adverse to the financial risk of a large purchase, due to the variable nature of their cashflow [51]. This is reinforced by findings that SHS purchasers were more likely to have a steady income source [53]. Therefore, alternative payment methods are needed for those with low or variable income that precludes the lump-sum purchase of solar products.

Payment Options

The need for financing or other flexible payment options is frequently cited in the literature [17,20,49–52,62]. The liquidity constraints of potential customers hinders the adoption of solar products [58]. Some researchers regard the lack of affordable finance as the main barrier to adoption of SHSs and the success of solar enterprises in-country [67,71]. The importance of financing schemes is also reflected by customers' desire for manageable monthly payments versus lump-sum payments up front [15,57,64].

Unfortunately financing is not available to most consumers in developing countries; in some countries as little as 10% of households have access to formal financial services [67]. Even those who do have access to these institutions would require a regular income stream and/or collateral to secure financing [62]. Furthermore, those who can secure a loan at a commercial bank may end up paying a high interest rate, which can range from 15% to almost 40%. The availability of financing for renewable energy technology is further limited by financial institutions who do not have a portfolio dedicated to these technologies, or who are not even familiar with the technologies [67].

Even if there were local financing options with low interest rates that would allow customers to make monthly payments, they still may not be tenable for many. Alstone, Gershenson, and Kammen stress the need for payments similar to current payment streams for kerosene and phone charging – smaller payments multiple times per week that may be better addressed by a pay as you go system [25]. Pode states that many customers could not handle fixed monthly payments given their variable and uncertain income, which would require a more flexible payment system [67]. Schäfer, Kebir, and Neumann reported another potential SHS financing issue, wherein the duration of payments is longer than the battery warranty period. These customers would have to either pay the up-front cost of a replacement battery or revert to using kerosene, while still being responsible for the remaining payments [59]. Even if all of these financing hurdles were overcome, the adopter would still have to have a favorable attitude toward utilizing credit for the purchase a solar product [14].

Regardless of these potential drawbacks, there is some quantitative evidence showing that making payments in installments greatly improves uptake of improved cookstoves. Levine et al. performed an RCT that tested the effects of payment options and free in-home trials on cookstove adoption in Uganda. They found that adoption was more than six-times greater among those who were able to pay in four weekly installments, relative to those who had to pay in full upfront [49]. The impediment of lump-sum upfront costs is further evidenced by the case of grid connection costs in Bolivia; when connection costs were amortized over five years, the number of new customers doubled [57].

In addition to financing being available to the purchaser, it should also be available to the retailer. Many retailers do not have the liquidity to purchase additional solar products until current inventory is sold [17]. This issue is likely compounded by retailers’ lack of familiarity with solar products, or the uncertainty of the salability of these products in a nascent solar market. Therefore, retailers also need increased awareness and financing options in order to make solar products more available.

2.4.4 Availability

The availability of a product is an obvious prerequisite to its adoption. Availability of solar products, or the lack thereof is seen as a major impediment in the development of a sustainable market for solar products [17,50,67]. In fact, current efforts are often unable to reach the communities that need solar products the most [51]. Another issue is the availability of after-sale service, such as installation, maintenance, and spare parts, which can affect consumer confidence when purchasing and lead to systems falling into disrepair [23,59,74]. Below we discuss the dimensions of availability affecting solar products and service, including market and distribution issues, and explore the geographic factors that are associated with availability of these products.

Market

The present status of the market for solar products in low and medium-income countries may be an impediment to product availability. A number of researchers cite poorly developed solar markets as a factor constraining the availability and adoption of these products [17,67,71]. The issue does not only lie with solar, as rural markets are poorly developed in general. In combination with high levels of poverty and a weak customer base, there is limited demand for solar products [20]. Additional market limitations come in the form of ineffective marketing and branding, and a lack of resources for scaling up, as well as a lack of expertise when products are sold through existing retailers [17].

While market issues limit the availability of solar products, the limited availability of solar products and accessories restricts further market development simultaneously. Solar products have a variety of applications beyond basic household needs. There needs to be a greater range of available accessories and appliances, because access to these complementary products can help drive adoption [23]. Furthermore, it is critical that high-quality products are available [61]. If businesses are only stocking the lowest-cost solar products, these products are more likely to be low-quality products, thereby contributing to the market spoiling issue.

Although the current market for solar products in developing communities is underserved and underutilized, this market has great potential for growth. In fact, the market may be expanding at a rate that is not yet well represented in the academic literature. There is some evidence of this expansion in recent reports from the Overseas Development Institute, Lighting Global, and the Global Off-Grid Lighting Association [12,30,75]. This growth is likely due to a technology push, whereby businesses actively create demand for solar technology [17], but it is also possible that demand has increased since 2014 and there is greater market pull for solar products.

Distribution

One of the primary obstacles to the availability of solar products is the difficulties faced in distributing these products. This is especially true in rural areas where electrification rates are lower, there are fewer alternatives, and there is a low likelihood of improving energy availability in the foreseeable future [17]. Distribution issues are primarily a result of the dispersed rural population and poor transportation infrastructure.

A number of researchers have cited the dispersed nature of rural households, and low population densities as a logistical challenge to distributing renewable energy technology in developing communities [17,50,51,59,66,70]. Additionally, urban based suppliers of renewable energy technologies may not be able to adapt to the needs of the rural population [67].

Poor transportation infrastructure is another major obstacle to distributing solar products in emerging markets [20,23,50,71,76]. McEachern and Hanson found that villages with the highest numbers of SHS users were accessible by a paved road [65]. Beyond transportation infrastructure, there are other infrastructure shortcomings that may affect the market for solar products, including unreliable grid electricity at production, distribution, and point-of-sale locations, and other issues with market and supply chain infrastructure [15,17,50,77]. As previously mentioned, Lay, Ondraczek, and Stoever found evidence of geographically clustered solar system in Kenya; they hypothesized that these clusters may arise, due in part to the availability of market and other infrastructure [54].

Distributed populations and poor infrastructure not only make distribution of solar products more difficult, but also more expensive [62,66]. The heavy weight of the lead-acid batteries needed for SHS increases the difficulty and cost of transporting these technologies [67]. This increases the amount of investment required and lowers the return. Another potential cause of the solar clusters seen in Kenya is possible lower costs of solar products in areas where the desired infrastructure was already in place [54].

Location

As previously mentioned, there is evidence of solar ownership emerging in clusters, and this may be a result of geographic variability in accessibility and infrastructure [54]. Some researchers have found adopters to be more likely to live near the electric grid [65,78]. Lay, Ondraczek, and Stoever found that approximately one third of SHS owners in Kenya also had a grid connection. These outcomes may be partly attributable to SHS dealers being more likely to operate near the grid [54]. Based on a literature review, Nieuwenhout et al. reported that most SHS purchasers live near dealers [79], though Rebane and Barham found the opposite to be true in Nicaragua [53]. Smith and Urpelainen found that both urban and rural households were equally likely to own a SHS in Tanzania [51].

There is not a clear relationship between solar ownership and location (rural, urban, near-grid, off-grid), which likely depends on the local context. It also appears to depend on the stage of the diffusion process, i.e. the timing and market maturity. In an analysis of SHS diffusion in 120 villages in Sri Lanka, McEachern and Hanson found that villages close to population centers with solar distribution hubs and loan offices were the first to adopt SHS; however, as time went on, solar companies increasingly targeted more distant villages. Ultimately, the remote villages had the highest SHS adoption rate, which is likely a result of greater demand due to the lower likelihood of the grid extending to these areas [65]. The difficulties faced when distributing these products to rural locations and selling them to underdeveloped markets require further consideration to ensure the successful dissemination of solar products for rural electrification.

2.5 Enabling Environment

In the context of the solar ToC, the enabling environment is composed of the external factors which most directly influence the adoption conditions, so they are an important step along the pathway to improve adoption conditions and increase solar uptake. The fundamental components of the enabling environment are: appropriate technology, which affects attraction and affordability; information systems, which affects awareness and attraction; and market infrastructure, which affects affordability and availability.

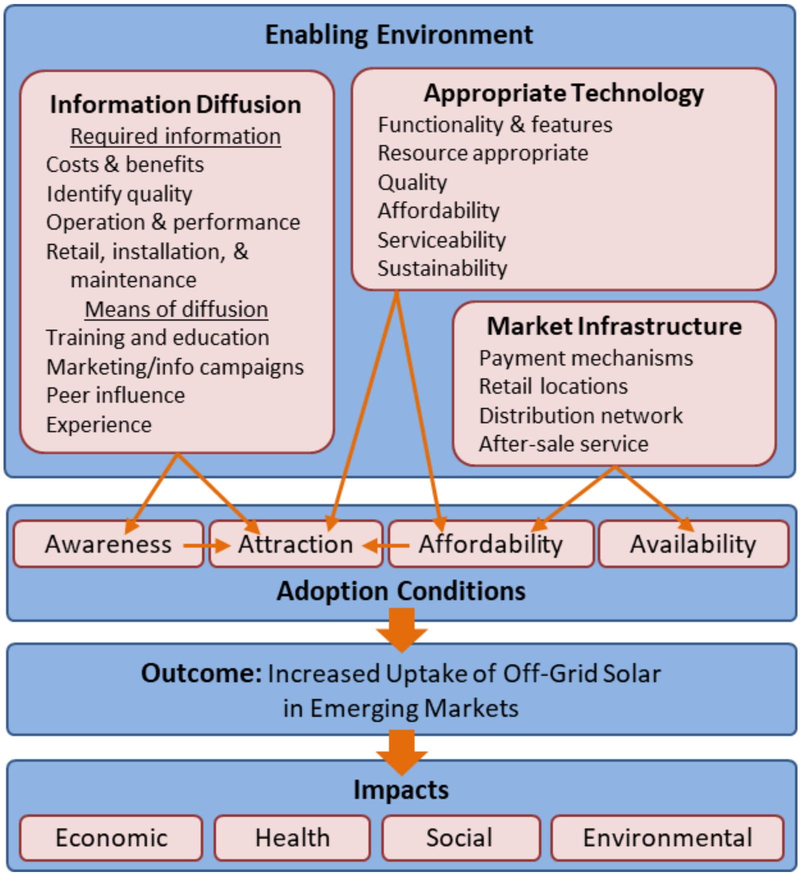


Figure 2.4: Theory of change diagram highlighting the enabling environment

2.5.1 Appropriate Technology

Appropriate technology is needed to make solar more attractive and affordable for potential adopters. The more compatible the technology is with adopters' values, experiences, and needs, the faster adoption will occur [14]. When designing an off-grid lighting products, the users' needs and preferences must be considered, to ensure that the technologies are compatible with local requirements [14,17,59,80]. This is problematic, because there is a relatively low understanding of user desires for technology in emerging economies [76]. This can be partly attributed to the high cost of good market research, which leads to the use of existing information or the opinions of experts [17]. This can lead to products that may not meet the requirements of potential adopters [17,21]. In this section, we will outline the main dimensions of designing appropriate technology which are seen as a universal guideline for developing appropriate solar technology, and some examples of context-specific design requirements that are not universally applicable.

Functionality and Features

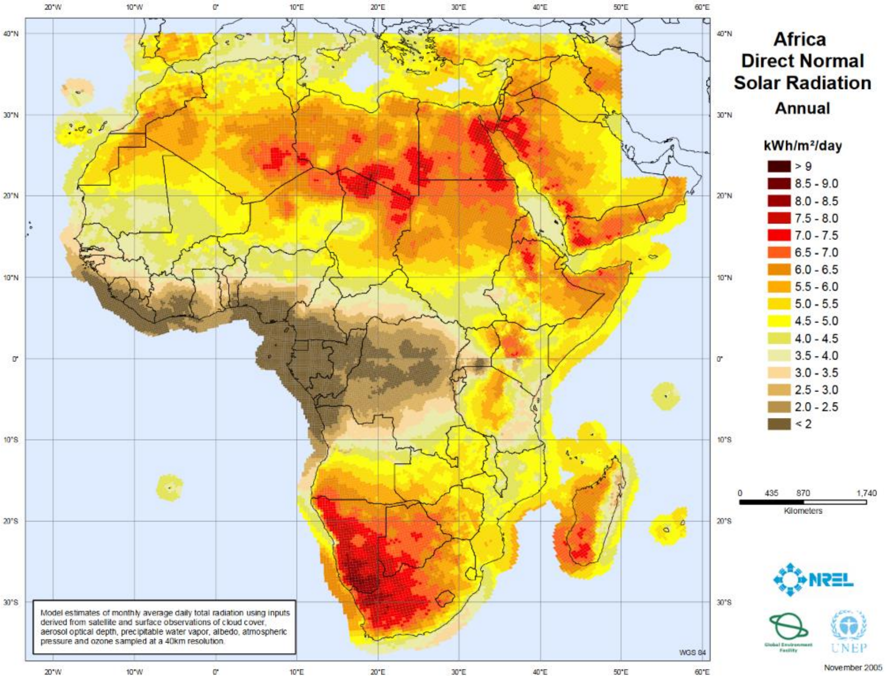
Though user preferences will vary from location to location, and local preferences should be further researched and assessed to maximize attractiveness, there are some universal design requirements. Solar products should be safe to operate and easy to use, given that rural customers may have limited knowledge of advanced technology [14,17,59,63]. It is also clear that potential users desire bright light, and dim lighting is a primary cause of dissatisfaction [60]. As such, one should not use dim kerosene lanterns as a benchmark for brightness [17], but it may be advantageous for solar lanterns to keep the familiar form factor of kerosene lanterns.

There should be a range of different product offerings available to meet the varying needs and budgets of consumers [19]. Some consumers may be primarily interested in light, so a simple solar lantern would be best for them [17]; some consumers may be interested in a solar rechargeable flashlight for checking on livestock [61]; many consumers will desire the ability to charge a mobile phone [50,61]; night market vendors or night fishermen will require extra bright lighting products [60,70]; prepackaged SHSs should be adaptable to the nature of rural households, which may be composed of multiple buildings separated by some distance [69].

There are additional design considerations which are often less tangible, but no less important to creating attractive solar products. One example is the desire for a more modern lifestyle, observed in Kenya; users desired a wall switch and a fixed lightbulb as they saw these as symbols of that lifestyle [23]. SHS kits often come with a length of wire which contains an inline switch and a simple bulb holder at the end, and it is meant to be tacked in place rather than permanently affixed. Such a product might not meet the aspirations of those interviewed in Kenya. Another aspiration is the desire to be able to own and power a television [50,73]. In short, users' specific needs and desires should be assessed in order to include necessary features in the product design.

Resource Appropriate

Solar technology must be adapted for the natural and man-made resources in areas where it will be deployed. For example, the intensity of the local solar irradiance must be taken into consideration when designing or selecting appropriate technology. Figure 2.5 shows the geographic variations in the estimated power density of the solar resource across Africa. There is a great deal of variability in the solar resource across the continent, and even within some countries; some areas receive less than one quarter the amount of solar radiation compared to other areas. Geographic variations in the solar resource influence whether or not solar technology is appropriate for a given location, and indicates sites where the technology is better suited.



Model estimates of monthly average daily total radiation using inputs derived from satellite and surface observations of cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmospheric pressure and ozone sampled at a 40km resolution.

Figure 2.5: Annual average direct normal solar radiation in energy per area per day (kWh/m^2/day) [81]

The available solar resource also affects solar home system and component sizing, and economic performance of the system. The energy density of the local solar resource is important knowledge for evaluating economic viability, and for specifying system and component sizes. A location with half the daily irradiance compared to some other location will need twice as much solar panel area to capture the same amount of amount of energy; however, this location will not need to double the battery capacity if the end-use energy requirements are the same. This is problematic because many SHS come prepackaged with a one-size-fits-all panel, battery, and other system components, so these systems are not optimized for the solar resource of a specific location – which will negatively impact the system performance or economic performance, depending on the location.

Another consideration for system sizing is seasonal and short-term weather variability, which is especially true in areas that have a rainy season. The system should be sized for the reduced solar irradiance available during the rainy season, otherwise customers may be dissatisfied with the system performance, and batteries could suffer from deep discharge [59]. In general, undersized systems that supply an inadequate amount of energy will disappoint customers [62]. In Bhutan, SHSs are underperforming expectations because the solar irradiance data was collected for a limited geographic and time scale, then assumed to be the same for the whole country year round [66]. Similar issues should be avoided through an adequate understanding of solar resource availability, which will then inform proper system sizing and set customer expectations.

Current and future grid availability is a man-made resource which affects the appropriateness of solar technology. If grid power arrives to an area where pay-as-you-go SHS are installed, SHS users may default on their payments in favor of a grid connection [29,65]. While there is some demand in areas where the grid is already present [54,65,78], these areas may not be the best target market for solar technology.

Quality

Product quality is a major concern, since low-quality products have the potential to hinder market development for solar products. Quality products will minimize premature product failure, which will help establish trust in the market [17]. Offering a warranty may or may not boost consumer confidence, but it should be a sign of a quality product, especially if consumers know how to make a warranty claim and that the warranty will be honored [70].

Many pico-solar products do not have the ability to prevent deep discharge of the batteries [61]. This is problematic because deeply discharging the batteries leads to shortened battery life, and batteries are the primary cause of premature product failure [17]. Therefore, the additional cost of battery protection circuitry could outweigh the cost of early product failure. Solar lanterns that contained protective circuitry still performed well after a year of daily use in Malawi [63].

Though SHSs should include a charge controller that prevents deep battery discharge, the batteries are still susceptible to damage when the installer does not include a charge controller, when it malfunctions, or when users bypass the charge controller to get additional runtime. Additionally, the charge controller should be designed to withstand the hot environments that may be present in SSA countries, and the effect of heat on batteries should be accounted for in the development process [59].

Another cause of product failures is water intrusion that leads to electrical failures. This can be a result of low quality housings that are brittle and easily broken, or that were not designed to the proper waterproof rating. Failures are also prone to occur if the product was not designed to be robust against drops and other normal wear-and-tear, or if it has poor quality solder joints [61]. Quality can be assessed, in part, by submitting the products for testing by Lighting Global, a World Bank program which supports off-grid solar market development. However, field tests should also be done, as lab tests may not adequately reflect real-world performance [15,44]. Finally, it may be advantageous to design products such that consumers can easily identify them as high-quality and distinguish them from potentially similar-looking low-quality products.

Affordability

Making products affordable to the consumer is an important aspect of appropriate design. Affordability is not only the upfront cost of a product, but also includes the longevity, and the maintenance and repair costs over its lifetime. A product that is cheaper, but fails sooner or requires more service, is less affordable in the long run. Thus, products should be designed or selected with quality in mind. Creating a quality product can be difficult when trying to compete in a market that is making products as cheap as possible to meet the willingness and ability to pay of the target consumers [17]. However, there is evidence that low-income consumers are inclined to pay a premium for quality products [15].

Consumers’ income and willingness to pay should be taken into account when designing or selecting off-grid lighting solutions [21]. A survey in Malawi showed that the price of a solar lantern was about half a month of income for lantern owners, while it was about 2 months income for non-owners [63]. In an RCT in Kenya, solar lantern uptake was 29% at the market price of $9, 37% when discounted to $7, and 69% when discounted to $4 [47]. Current location specific assessments of willingness to pay should be made.

Solar product design should include features that increase willingness to pay. For example, a contingent valuation survey in Kenya showed higher willingness to pay for a SHS among people who reported an interest in starting a business [57]. Additionally, sizing solar systems to be appropriate for the needs of different household needs may increase willingness to pay, especially where economies of scale make the system more cost-effective for large households [51]. In general, developing an appropriate design that addresses customers’ needs and desires should increase willingness to pay.

Serviceability

Another important design consideration is serviceability. Unresolved technical issues result in unsatisfied customers [82], an outcome that could be mitigated by creating products with serviceability in mind. Difficulty reaching remote areas means that provisions should be made to simplify serviceability, so that basic service and repair can be done at the local level with limited technical skills [21,59]. Serviceability would be further enhanced by incorporating locally available materials and local knowledge [59].

Another means of improving serviceability is to use standardized components across a range of products, to limit the amount of spare parts and specialized skill needed [17,21]. This is especially true for batteries, which are rarely serviceable on pico-solar products. Because battery failure is a common and inevitable mode of failure, product design should allow for simple battery replacement using commonly available rechargeable batteries [63].

Sustainability

Design for environmental sustainability may or may not be of value to the end-user, but this important criterion should be considered when creating off-grid solar products. The design should employ materials that minimize the environmental impact of the device. The product should be high quality and easily serviceable so that electronic waste, such as batteries, is minimized [17]. Sustainability is further enhanced by incorporating local materials, where possible [21].

2.5.2 Information Diffusion

Providing reliable and accurate information on solar technology is important to enabling adoption, through increased awareness and attraction [15,25,51]. The adopter will seek information at various stages of the adoption process in order to minimize their uncertainty of a new technology [14]. Below we will discuss the types of information that are required and the means of disseminating that information.

Required Information

Consumers require information on costs and benefits, how to identify product quality, and how to use and perform basic maintenance on the product. Retailers will require information on how to successfully operate a solar business, and technicians will need information on how to install, service, and repair solar systems.

Costs and Benefits

Awareness of a product and its benefits is paramount to make the product attractive to customers, increase interest and confidence in the innovation, and create market demand [15,17,21]. The economic advantages of solar products relative to alternatives are a key piece of information that the consumer must understand [15,63]. As mentioned previously, purchases of kerosene for lighting can consume a significant proportion of household income, and a solar lantern can reduce these expenditures significantly, while providing brighter light for longer periods. In addition to the ongoing expense, kerosene has a number of other disadvantages that should be communicated to potential adopters, including health and safety concerns [4,5] and issues with the quality of light [74].

Customers should have knowledge of the costs in addition to the benefits of solar products, including potential maintenance costs. They should also be informed about potential drawbacks and limitations, including expected runtime and the seasonal variation thereof. Once consumers have a realistic understanding of all the costs and benefits they can make a well-informed decision about adopting solar technology.

Identify Quality

One of the current issues with the solar market is a lack of information about product quality, giving rise to information asymmetry [49,61]. Consumers are aware that there are low-quality products on the market, but they are unable to identify these products and differentiate them from high-quality products. Customers should be given information that will help them differentiate product quality, such as a clear symbol on the label of products which are quality certified, so that they have more confidence in solar products and are less hesitant to make a purchase [61]. Customers who are empowered with the ability to identify product quality will not only be more likely to make a purchase, they will also be willing to pay a higher amount for a quality product [61].

Lighting Global has been successful in improving product quality through testing and certification, but they do not currently have a logo or “seal of approval” for use on product packaging as an indicator of quality. In the future, consumers should be provided with unambiguous indicators of quality, like a seal of approval, which could increase their attraction for high-quality products. Consumers should then be made aware of the existence of these indicators, how to positively identify them, and where these high-quality products are available.

Operation and Performance

Misuse by the owner is a major factor that leads to early product failure, so it is important that owners are properly informed about how to use their solar products [17,19]. This includes information about the potential safety hazards of electrical systems that are used improperly [15].

In addition to understanding the how to operate their solar products, users should be taught the basics of how the system functions [62]. This knowledge could help with identifying and troubleshooting problems in the future. Users should also be educated about devices that are compatible with their systems and how much energy these devices will use [15]. By better understanding these aspects of solar systems, early product failure will be reduced, and these systems will be used more efficiently and effectively.

It is important that solar adopters have realistic expectations of the performance and limitations of their products [15,61,62]. If users are given incorrect or incomplete information about their system's operation, they will not be able to use it for their intended purpose, or will otherwise be disappointed in the product [59].

Retail, Installation, and Maintenance

Developing local capacity, including business, installation, and maintenance skills, is another important component of creating a sustainable rural energy systems [83]. Local capacity has not been increasing at a rate that matches increasing demand for solar products [69].

Well informed local retailers are critical to the growth of the solar market. Often times solar products are sold through existing retailers who may need more knowledge to effectively run a business selling solar products [17]. The entrepreneurship skills of local solar retailers should be enhanced, and specific knowledge pertaining to successfully marketing and selling solar products in their target market should be provided [17,20,63]. Understanding the benefits of selling quality products, being able to identify these products, and passing that knowledge to the customer are key components of the necessary expertise [61].

There is a gap in the knowledge transfer between producers of solar products and the technicians that install these systems, which can lead to improper installation. Examples include panels installed in the shade or at the wrong angle, improper sizing and combination of components, and even installation of SHSs without charge controllers or with automotive batteries [56,59]. Not only is there a shortage of knowledge among existing technicians, but there is a shortage of technicians in general, especially in remote areas [56].

Users should also be made aware of maintenance issues and be able to perform basic maintenance and troubleshoot basic problems. In a survey of SHS users in Tanzania, none of the households had received information on basic maintenance, such as cleaning dust off the panels and maintaining the water level in the batteries [56].

Means of Information Diffusion

Now that we have identified the information relevant for enabling the adoption of solar products, we will discuss ways to disseminate that information. Outlets for such information include training and education, marketing and information campaigns, peer influence, and first-hand experience.

Training and Education

In order to address the shortage of human capital, long-term investments in training and education programs for renewable energy systems is needed [19–21]. Technical schools, such as the one Simiyu et al. investigated in Kenya, are necessary to build the knowledge and skills needed to support the market for solar products; this ten-day program consists of theoretical and practical lessons, including the basics of solar operation, sizing, and installation, as well as operation and maintenance information to pass on to the end-user. To be in step with the Kenyan solar market, a section on solar lanterns was added, including assessing brightness, and how to disassemble and repair solar lanterns [69]. Technical schools across Sub-Saharan Africa should adopt solar focused curricula, such as this.

Information about solar systems can also be disseminated to a wider population through primary and secondary school curricula. These lessons could educate the youth about the various benefits of renewable energy options, the theory of solar PV operation, and other school appropriate knowledge. Sunny Money, an NGO working to distribute solar lanterns in SSA, operates through local primary schools. In this way, they are able to provide information about the technology and its benefits [84].

Less formal means of education, such as community based workshops and physical or digital guides, could be an effective means of providing information in the short term. These sources could effectively communicate basic information on installation, use, preventative maintenance, and repair. Additionally, graphical maintenance and repair guides could be provided to locals who have general technical knowledge [17]. User manuals should also be provided to consumers in a format that is easily understood, so they are aware of any required maintenance, and can troubleshoot basic problems. Relevant information should also be provided by businesses to users and installation partners as part of the transaction process.

Marketing & Information Campaigns

Marketing and awareness campaigns are needed to help consumers make rational choices regarding their energy sources [21]. The solar market is hindered by ineffective branding and marketing, which is often left to retailers that may lack the skills and resources needed to properly market and sell these products. The importance of marketing needs to be communicated to those in the value-chain, and the ownership of marketing responsibilities needs to be clarified [17].

Marketing for solar products can occur through media outlets, such as television, radio, and newspaper, but these communication channels can be costly [15]. The specific means of undertaking marketing or information campaigns in emerging markets is beyond the scope of this paper, but is well represented in the literature [85–90]. Because consumers are subject to many false marketing messages, information from traditional sources may be viewed with skepticism

[49]. Additionally, marketing efforts may only result in temporary increases in adoption, and sustained adoption will only occur if the product is compatible with local preferences [80].

Nevertheless, attempts should be made to employ effective marketing and branding campaigns. Mass media is an important means of providing information, and is especially influential in the early stages of adoption [14]. Manufacturers of high-quality products should brand their products such that they are recognizable and distinct from other brands on the market [61]. Consumers should be made aware of product certifications that can help them identify quality products and gain confidence in their performance [17].

Peer Influence

Another means of information dissemination occurs through peer influence, which can occur through observation, word-of-mouth, and social pressure [19]. Conventional marketing channels are expensive, unlike peer-to-peer communication – which has previously been employed by projects in Uganda and Bangladesh [15,67]. Rogers states that mass-media is a more effective means of diffusing knowledge of a new technology, but that peer influence is a more effective means of shaping attitudes about a new technology [14].

As previously mentioned, there are instances of solar technology being adopted in a geographically clustered manner, and this could be a result of peer influence affecting the diffusion process [54]. Graziano and Gillingham also found significant clustering of solar systems in Connecticut, which they determined are not the result of income or population distributions. The results of their study suggest that the clusters are a result of social interaction and visibility of installed systems [91]. In a study of knowledge related to solar technology in Nicaragua, Rebane and Barham found that the presence of SHS in an area is the strongest predictor of solar knowledge. These findings suggest that solar clusters and exposure to nearby systems is likely to have has an impact on the diffusion of information on solar technology [53].

In addition to the effect of peer influence suggested by solar clusters, there is direct evidence that peer networks are an important source of knowledge. SHS users surveyed in Kenya most often learned about these systems from friends, relatives, and neighbors [78]. Nieuwenhout et al. carried out a literature review on solar PV in various developing countries, and found that the most effective ways of spreading awareness are through interpersonal communication and observation of installed systems [79]. There is evidence that peer influence is more convincing and more effective at achieving understanding, compared to traditional channels [15]. However, peer networks may simply be more influential when the benefits and drawbacks are not as obvious [80]. It is important to note that even non-users are a significant source of information diffusion, especially when there are few users in a community [92].

There is some evidence that peer influence may affect adoption behavior in addition to increasing knowledge. In general, peer influence is more persuasive in the decision to adopt a new technology, compared to mass-media [14]. Though not specific to solar or developing communities, Skinner and Staiger found that a measure of social capital is one of only two factors associated with the rate of adoption of the four innovations studied: computers, tractors, hybrid corn, and beta-blockers [93]. In Connecticut, time and distance dependent neighbor effects influencing the rate of solar adoption [91]. In rural China, Pan and Veronesi found that farmers who know more adopters of biogas technology are more likely to adopt. They also found that trusted individuals, such as friends and relatives, affected adoption through the provision of information, while less trusted individuals affected adoption through their adoption behavior [94]. However, these studies may not adequately address the challenges in identifying peer effects, namely correlated unobservables, homophily (self-selection of peers, who may have similar traits), and simultaneity (one affects their peers and their peers affect them simultaneously) [91,95].

Furthermore, there are other studies which did not find peer influence to affect adoption behavior. In a study of the diffusion of microfinance, Banerjee et al. develop a model that accounts for diffusion of information and diffusion of behavior separately; they found that neighbors only act as a source of information and do not directly influence adoption through endorsement [92].

Similarly, in a study on cookstove adoption in Uganda, Beltramo et al. found that peer effects can increase the odds of strongly favoring the cookstove, but this does not appear to translate to increased cookstove adoption [95]. Because there is limited evidence on the effect of peer influence on the adoption of solar technology in developing countries, it is difficult to draw a conclusion. Regardless, there is substantial evidence that peer networks are an important means of information diffusion across a range of innovations.

Unfortunately, negative information can also pass through peer networks just as easily, which could lead to decreased adoption. In fact, Miller and Mobarak found that households are more likely to acquire negative information about cookstoves from peers, and that negative information is more influential when customers are inherently distrustful of new products [80]. This is especially problematic for peer influence on solar products given the widespread quality issues discussed earlier.

The slow rate of information diffusion is another potential downside to peer networks [17], though there is potential for it to be a rapid process [58]. Information diffusion through peer influence is a naturally occurring process, but there are ways for practitioners to tap into peer networks and potentially accelerate the diffusion process. One means of activating peer networks is through opinion leaders – people who are influential in their community [14]. These opinion leaders could be provided with information, but it may be more effective to provide them with a discounted or complementary solar product [65]. Opinion leaders are not universal and will need to be locally identified, but they may include local government or religious leaders, wealthy individuals, and elders, among others [14]. Another possible way to access peer networks is by installing and showcasing solar technology at a public venue, such as a house of worship, so that the community may experience the benefits [65].

Experience

First-hand experience with a product is possibly the most effective way of communicating its relative advantages. Technological innovations are more likely to be adopted if they can first be experienced, even on a limited basis [14,15]. If consumers are offered an in-home trial, they are able to assess fuel savings, brightness, and product quality through experience. Sunny Money operates through primary schools and allows student to check out solar lanterns for studying at home. Households are able to gain knowledge about the product, and are more likely to purchase a solar product [96]. Simply being able to handle a solar product increases willingness to pay, but an in-home trial increases willingness to pay even more [61]. The effect of being able to experience a product before purchase is further illustrated by the RCT Levine et al. carried out in Uganda; purchase of improved cookstoves was about seven-times higher with a no obligation in-home trial, and about eleven-times higher with an in-home trial and four weekly payments [49].

2.5.3 Market Infrastructure

Certain physical and non-physical infrastructure is needed to make solar products available and affordable. A well-developed solar industry will not only make products more widely available, but will also help lower prices for solar products [50]. A healthy and functional solar market will have a structure that includes financing or pay as you go (PAYG) options, retail locations, a functional and efficient supply chain, and services for installation, maintenance, and repair.

Payment Mechanisms

Many people in Sub-Saharan Africa cannot afford the upfront cost of solar products, and there are limited options for financing [67]. Many consumers require payment schemes that are similar to their current spending patterns for kerosene and other fluctuating expenses [15,23,25,57,67]. In addition to not resembling current expenditure streams, bank loans are hard to get for many people in developing countries, and have interest rates from 15% to 40% [67]. Appropriate financing options should be available at local finance institutions that are easily accessible, in order to facilitate purchases and the development of the solar market [20,70].

Microfinancing is a broad term for a number of informal alternatives to bank loans, generally characterized by less stringent requirements and smaller loans amounts, which promote financial inclusion. Off-grid renewable energy systems are increasingly linked to microfinance [59,63]. Growth of the SHS market in Bangladesh was driven in part by preexisting microfinance structures [67].

Savings and credit cooperatives (SACCOs), which are similar in principal to credit unions, represent one means of obtaining microcredit in emerging economies. In additional to having more flexible loan requirements and repayment terms, SACCOs have interest rates significantly lower than banks in the region [67]. A program in Kenya allows salaried employees to have SHS payments deducted from their monthly paycheck, which gives high confidence in lending [82]. Unfortunately, interest rates can still be high with either these schemes, and these programs are limited to co-op members and salaried employees, respectively [67,82].

The rent-to-own or pay-as-you-go (PAYG) option for solar products allows customer to pay in regular installments until the product is paid off – microcredit offered at the point of sale. This increasingly popular business model makes solar energy accessible to many consumers in Sub-Saharan Africa [29,52]. In 2015, there were at least six companies working to establish PAYG options for SHS sales in Kenya alone [82]. Mobisol, a German solar company operating in East Africa, offers their SHS with PAYG options, which pay off the system over a period of three years with a total payment 25% higher than the cash-and-carry price; thus the interest rate is relatively reasonable at less than 10% per year [97].

In three research studies that used PAYG options in Malawi, Uganda, and Kenya, repayment rates were 80%, 92%, and 100% respectively. The effective interest rate was about 6% in the first study, while interest was not charged in the latter two studies [49,60,63]. In the study in Malawi, retailers were not happy with the PAYG option, in part because it was difficult and time consuming to try to collect payments from the 20% of people who defaulted. Additionally, demand for solar lanterns was greater than supply in this instance, so retailers made preferential sales to those who could pay cash [63].

Current PAYG models usually include the ability to make/receive payments remotely. With the majority of households in SSA having a mobile phone, and most cellular providers offering mobile payment services, making payments via mobile devices is becoming increasingly common for off-grid PAYG [25,29]. In Uganda, Eder, Mutsaerts, and Sriwannawit found that 28 of 31 interviewees said that they would have no issues with mobile payments for their microgrid service. Those interviewed believed mobile payments are safer than cash, that they would save them time, and that this payment method is very transparent with little ability for fraud [15]. In addition to being able to receive payments remotely, current PAYG models include some means for disabling the system if payment is not received. Though this can be done manually in person, PAYG systems are often able to be disabled remotely via a connection to the mobile network or locally with Bluetooth [29].

Another emerging business model is the fee-for-service or solar-as-service (SAS), where consumers pay monthly to rent a solar system owned by an energy service company, i.e. a perpetual lease. In fact, it was the most frequent ownership model represented in a systematic review of solar energy in low and middle-income countries [19]. Because the lease term is indefinite, SAS providers can charge lower monthly payments relative to PAYG schemes. Additionally, customers do not have to worry about their system breaking, since the energy service company will take care of it. However, customers can have a cultural preference for owning the system, favoring the PAYG option [29].

In addition to consumer finance, distributors and retailers need access to credit. These businesses have limited liquid assets, so they may find it difficult to reliably distribute or stock solar products. The resulting issues with product availability creates problems with customer satisfaction and/or loyalty, further hindering the market for solar products [17,67]. However, not all retailers will find financing schemes desirable. In Malawi, retailers were reluctant to use credit available to them from a solar cooperative, instead preferring to pay cash [63]. As an alternative, distributors could collect payments from the retailer after the products are sold, rather than up-front.

Retail Locations

Local vendors are a vital component of a successful solar market, and they are a limiting factor where there is unmet demand [63]. Often times, solar products are sold through existing retailers [17]. Sometimes even villagers themselves are undertaking marketing and distribution of solar products [67]. These local retailers are better equipped to adapt to the local context, and such a distribution model increases the number of outlets where solar products are available [15]. Additionally, consumers may have greater trust for local providers [57]. To further enhance trust, confidence, and loyalty, vendors should stock high quality products, even if they cost more. Additionally, retailers should seek out information that will improve their effectiveness in solar product sales.

Physical retail locations are not always necessary; in the Avon model employed by Solar Sister, women are provided training and a “business in a bag,” and sell solar products door to door [52]. A similar sales agent model is widely employed due to the ease of establishing new outlets, and the lower cost relative to a physical retail location. One potential issue with this model lies with difficulties in reaching rural areas and corresponding difficulties for customers to follow up with the sales agent. Also, limited demand for solar products make these agents unable to sustain their business through solar sales alone [17].

Distribution Network

A reliable distribution network is essential to supply high-quality solar products to meet growing market demand. In-country distribution networks should expand their ability to reach remote areas in order to increase market coverage [50]. There should also be provisions for including spare parts and warranty service in the distribution network [63]. Infrastructure shortcomings and the financial capacity of the businesses in the supply chain are the main impediments to its functionality [17,50,76].

It may be possible to leverage existing distribution networks for more efficient, reliable, and cost effective product supply [17,70]. For example, the Coca-Cola Company has an extensive supply network in SSA which serves rural and remote locations through over 3,000 independent local distributors utilizing their Micro Distribution Center model [98]. Solar products and packaging could be made compatible with the existing beverage crates, so that delivery trucks can be loaded with a combination of soda and solar for delivery along the usual supply routes. Even if the physical distribution networks cannot be co-opted, existing logistic and distribution expertise can be applied to off-grid solar supply chains. The Coca-Cola Company has shared their expertise with governments in several SSA countries, to the benefit of medical supply chains in those countries [99].

Further advantages in cost and reliability may be realized through the integration of distribution networks in neighboring countries. Local production and/or assembly of products and system components would help contribute to a robust supply chain [50]. If production facilities were established in country, parts and service would also be more locally accessible [17,59]. The wide availability of communication technologies has the potential to integrate and streamline distribution networks, including tracking products [25].

After-Sale Service

After-sale service, including installation, maintenance, and repair services, are an important part of ensuring the long-term sustainability of the solar market. Currently, these services are lacking, affecting performance and reliability, and causing systems to fall into disrepair [19,20,56,59,67,74]. Too much emphasis is placed on design and sales, and not enough attention is given to post-sale service [17].

One solar product provider in Tanzania recruits local motorcycle taxi drivers to work as part-time repairmen. They are provided with training and a smartphone. When a customer has a maintenance issue, a nearby motorcycle taxi is dispatched to the customer via the smartphone, which then provides a visual troubleshooting and repair guide, based on the customer’s complaint (interview). Two solar providers in Kenya utilize locally available technicians, while a third company attempts to assess and repair systems remotely, using their dealer network to return and replace faulty systems when necessary [82].

The knowledge of how to service and repair solar systems will be ineffective without access to the necessary parts. It can be difficult to acquire spare parts, especially in rural settings, and this has contributed to failed systems [59,66,67]. Options for returns and warranty service should also be more accessible [17,63]. The availability of these materials and amenities would help enhance perceptions of quality for solar products.

2.6 Change Agents and Their Roles

Change agents are the actors and stakeholders who are capable of cultivating an *enabling environment* for increased solar adoption through their actions and interventions. Change agents primarily influence the adoption conditions by contributing to an enabling environment, as seen in Figure 2.6, though in some cases they can directly influence the adoption conditions (e.g. government influencing affordability through subsidies or reduced tariffs, not shown in figure). In this section we identify the relevant change agents, identify the primary roles that need to be filled, and rate the interest and influence for each of the change agents to fulfil these roles. Here, we outline the roles in a general way because the change agents themselves will be better equipped to identify specific programs and interventions based on their organization’s mission and strengths.

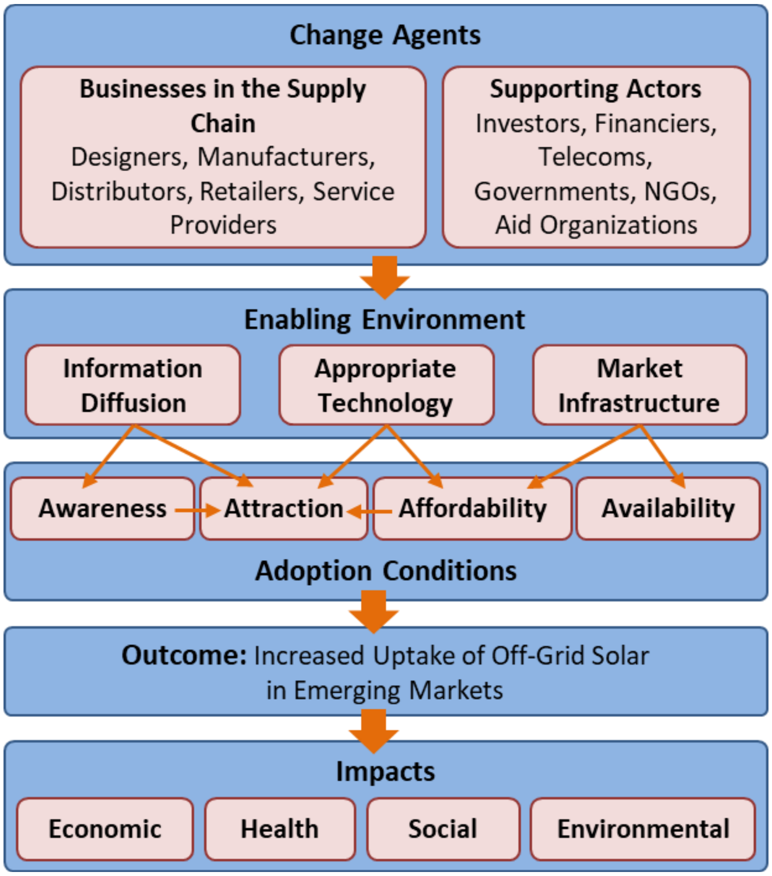


Figure 2.6: Theory of change diagram highlighting change agents

Our discussion of the relevant change agents is partly organized along the supply chain, similar to [17]. The primary businesses in the solar supply chain are designers and manufacturers, distributors, retailers, and service providers [17,29]. However, a single business can encompass more than one, or even all of these functions [29]. There are a number of change agents which are not part of the supply chain, but they have the capacity to support businesses in the supply chain. These supporting actors are investors and financiers, governments, non-governmental organizations, bilateral and multilateral aid organizations (aid orgs.), and mobile telecommunication companies.

We used a stakeholder mapping technique to identify which of the above stakeholders should be engaged as part of the planning strategy for a given program or intervention. A stakeholder map is a four-quadrant plot of all relevant stakeholders, and they are located based on their level of interest, from low to high on the x-axis, and their level of influence, from low to high on the y-axis. Stakeholders who land in the upper-right quadrant should be engaged as part of a program, and those in the upper-left or lower-right quadrant should be kept informed. Because all of our stakeholders and role would not fit in a single stakeholder diagram, we have created a matrix (Figure 2.7) of mini stakeholder diagrams estimating each of the actors' interest and influence for each of the roles that may be applicable to them. Though a stakeholder's interest and influence are usually rated on a continuous scale, we are simply representing them as high or low, since they are subjective estimates.

			Businesses in the Supply Chain								Supporting Actors									
			Designers & Manufacturers		Distributors		Retailers		Service Providers		Investors & Financiers		Consumers and Local Facilitators		Governments		NGOs & Aid Orgs		Telecommuication Companies	
		Influence	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Appropriate Technology	Understand user needs	High		x		x		x		x				x						
		Low																		
	Characterize local resources	High		x	x															
		Low					x		x											
	Ensure product quality	High		x		x														
		Low						x		x										
	Distinguish high from low-quality products	High		x				x		x										
		Low																		
	Ensure serviceability and sustainability	High		x																
		Low								x										
	Receive ongoing feedback from customers	High		x		x		x		x				x						
		Low																		
	Set technical standards/product testing	High		x							x					x		x		
		Low																		
Information Diffusion	Marketing and information campaigns	High		x		x					x					x		x	x	
		Low						x												
	User/service manuals	High		x																
		Low						x		x										
	Provide information/education/training	High		x						x						x		x		
		Low			x			x						x						
	Investments in education and training	High														x				
		Low																		
	Seek out education and training	High						x		x				x						
		Low																		
	Provide information at the point of sale/service	High						x		x										
		Low																		
	Help identify quality products	High		x				x		x										
		Low																		
Market Infrastructure	Reliable supply/distribution/stock	High		x		x		x							x					
		Low																		
	Increase geographic reach	High		x		x		x												
		Low																		
	Increase access to parts and service	High		x		x		x												
		Low																		
	Enable payment mechanisms at point of sale	High	x		x			x				x								x
		Low																		
	Enable payment mechanisms for retailers/distributors	High	x		x							x								
		Low																		
	Shared distribution/retail network	High				x														x
		Low																		
	Policies that attract buinesses	High														x				
		Low																x		
	Access to capital	High										x				x		x		
		Low																		
	Financial guarantees	High														x				
		Low																		
	Address market shortcomings	High													x			x		
		Low																		

Interest

Figure 2.7: Matrix showing the main change agents, and qualitatively rating their influence and interest in the primary roles associated with positively affecting the enabling environment for solar adoption.

Designers and Manufacturers are largely responsible for appropriate technology because they have high interest and influence in each of the main roles associated with appropriate technology. It is very important that all of the businesses in the supply chain understand the needs of the user, implement a way to receive feedback from customers, and share that information with other actors in the supply chain. Since the retailer has direct contact with the customer, they could be the point of contact for receiving feedback from customers. They are also key in helping customers distinguish high quality products from low quality products, but they must be properly informed in order to do so. Most of the businesses in the supply chain should make contributions to information diffusion. Businesses in the supply chain are also critical to many roles in market infrastructure, as they are the basis of this infrastructure.

Investors and financiers are market-based actors that support businesses in the supply chain by providing them with debt and equity financing, so that these businesses have the resources necessary to fulfil their roles. This is one of the most critical roles, but it is currently one of the biggest obstacles to the growth of the off-grid solar market [100]. Governments may be the source of significant impediments, such as political and economic instability, but they have the power to be a key player in enabling solar adoption.

Non-governmental organizations (NGOs) are philanthropic and not-for-profit organizations that are independent of governments, such as the Bill and Melinda Gates Foundation. Bilateral aid organizations which receive funding from one country (e.g. United States Agency for International Development, Department for International Development – United Kingdom) and multilateral aid organizations which receive funding from multiple countries (e.g. World Bank, United Nations Development Program) can be NGOs or governmental agencies that focus on human and economic development around the globe. These actors can also fall into the category of financiers, as in the case of the World Bank and International Monetary Fund. The main role of NGOs and aid orgs is to fill the roles that are neglected by other actors, who may be unreliable, ineffectual, or unwilling to take the lead role. For example, due to the current shortcomings with private-sector investment, aid orgs will need to provide financial support until the solar market is better established. In this way, they are instrumental in priming the market, making it more attractive for businesses and the other supporting actors to fulfil their roles in the future.

Mobile telecommunication companies (telecoms) enable payment mechanisms for solar products through mobile payments, which can be SMS based [29]. They can also use their brand recognition and distribution networks to contribute to marketing efforts and building supply lines for solar products. Consumers themselves and local facilitators are also important for enabling appropriate technology by providing feedback, and for participating in information diffusion by receiving relevant knowledge and sharing it with peers.

Coordination and collaboration is needed among the relevant change agents, because the adoption conditions should be addressed simultaneously to maximize the uptake of off-grid solar products. This is also evidenced by Figure 2.7, which shows that a given role may have more than one actor with a high level of interest and influence. Additionally, there may be actors who are unable or unwilling to fulfill their roles, so other actors will need to identify these shortcomings and address them. For example, local retailers are important actors for a number of roles, but they may not have the power to carry out some of these roles. These actors need the support of other actors to provide financing options for customers, maintain an adequate stock of solar products, and advertise these products. Much of this support should come from financiers and businesses in the supply chain, as these actors stand to benefit from having more effective retail outlets. These issues are non-existent for businesses that are integrated along the supply chain, from development to retail.

2.7 Conclusion

The primary objective of this paper was to use the theory of change methodology to build a practical understanding of the adoption process for off-grid solar PV technology in Sub-Saharan Africa and other emerging economies. We developed a holistic and actionable theoretical framework that elucidates the fundamental mechanisms which drive solar adoption in SSA. Our

ToC provides foundational knowledge of the solar adoption process, which can be built upon by actors who can influence the change process. For example, the relevant change agents can use our generalized, sectoral-level ToC to guide their development of an organizational or project-level ToC that they can use for strategic planning and developing monitoring and evaluation protocols. In a more applied sense, the ToC can help guide research that identifies the drivers and barriers to solar adoption, then help develop appropriate interventions that address the barriers, enhance the drivers, and ultimately increase solar adoption.

The secondary objective was to familiarize a wider audience with the principles and process of developing a ToC through the example provided in this paper. In doing so, we demonstrated how the ToC methodology can yield a comprehensive yet elemental understanding of a complex change process. We also showed that the Four A's framework within our ToC fundamentally encapsulates the broad range of factors that drive or prevent solar uptake, since it adequately encompassed the myriad adoption conditions identified in the literature. Our theory of change is likely to be relevant to adoption of other technologies in emerging economies, because of its elemental nature.

There is limited evidence on the specific actions that will lead improvements in the enabling environment and increased solar adoption in emerging economies. This ToC serves as a guide for gathering such evidence, since it provides valuable insight into the change process. The Four A's should be used to frame research to determine what issues need to be addressed from the perspective of the adopter. Once any deficient adoption conditions are identified, the enabling environment (factors) will guide change agents toward identifying appropriate actions and developing effective interventions. The outcome of these interventions should be rigorously evaluated in order to build evidence that can be used to validate and revise the ToC, and assess its real-world utility.

Even if we confirm that this ToC is a valid and useful starting point for relevant actors to develop effective interventions, off-grid solar is not necessarily the best solution for achieving energy access in all contexts. While solar is expected to have a number of significant impacts and enable advancement in other areas critical to human development, it is not a development panacea, and increasing solar use or energy access in general may not be the most efficient way to achieve various economic, health, social, and environmental impacts. Thus, it is imperative that change agents working in this field have robust monitoring and evaluation plans, not only for the immediate outcome, but the short and long-term impacts. Such evidence will help determine the most efficient ways of achieving a desired impact.

3 Drivers and Barriers of Off-Grid Solar PV Uptake in Northern Tanzania

Kyle M. Karber, Katherine L. Dickinson, S. Revi Sterling, Michael P. Hannigan

3.1 Abstract

In Physics, energy can be thought of as the capacity to do work, and this definition is no less true in the context of poverty; electrical energy is a fundamental ingredient for working toward economic, technical, gender, and human development on a global scale. The dearth of energy access in Sub-Saharan Africa, including Tanzania, is a major impediment to realizing a future without poverty. As such, our research sought to identify the drivers and barriers of solar PV adoption in order to increase energy access in Tanzania and beyond. We used the Four A's—awareness, attraction, affordability, and availability—to frame our assessment of the state of the solar market in the Arusha and Kilimanjaro regions of Tanzania. Through survey research, we found that attraction was a major driver of solar adoption. Availability was not a significant barrier, probably thanks to the actions of major international solar retailers in the area. Affordability was not a significant barrier for the majority of our sample, thanks to payment plans for solar home systems, and the favorable economics of solar lanterns. Despite this, affordability is still a barrier for the poorest of the poor. A lack of awareness of the benefits of solar, especially financial benefits, appears to be one of the biggest barriers that remain. We recommend that stakeholders disseminate information on the financial benefits of solar products, and make payment plans available on lower-cost solar products, not just solar home systems.

3.2 Background and Motivation

Modern energy services are critical to improve quality of life and enhance human development in the Global South. A country's access to electricity is positively related to development indices for gender equality, education, poverty reduction, and maternal mortality. If used efficiently, even the first few watts of electricity have high marginal benefits for household health, education, and poverty reduction [25].

In Tanzania, access to electricity remains low. In 2016, the electrification rate in mainland Tanzania was 32.8% overall and 16.9% in rural areas (including grid and solar power) [101]. The estimated cost to extend the grid to rural areas ranges from 550 to 4300 USD per customer, with an average of 1547 USD, in 19 different regions examined in Tanzania [102]. As a result, grid expansion remains slow, with access increasing from 5.7% to 6.6% in rural areas between 2012 and 2016 [101,103].

Households require energy to provide several basic services, including cooking, lighting, and heating (in some climates). In the absence of clean energy sources, households rely on fuels and technologies that have significant health and environmental impacts. For example, use of solid fuels for cooking contributes to household air pollution which is estimated to cause 4 million premature deaths per year [104]. In the case of lighting, 22% of Tanzanians turn to kerosene and 45% use disposable or rechargeable batteries for light [101].

There are many disadvantages to kerosene lanterns, including indoor air pollution [4,5], safety risks [4,5], dim flickering light [74], cost [105,106], and greenhouse gas and black carbon emissions [6]. As such, the World Health Organization Guidelines for Indoor Air Quality discourage the use of kerosene [7]. Battery powered light sources introduce significant ongoing expenses and environmental problems with disposal [107].

Solar photovoltaic (PV) lighting products (henceforth referred to as solar) may be a viable alternative for off-grid populations in Tanzania. There are many benefits to using solar over kerosene lanterns: zero emissions at the point of use, no safety concerns, and brighter light than kerosene lanterns. Additionally, solar has less waste compared to battery-powered lights. It is estimated that a 13 USD solar lantern would pay for itself in kerosene savings in three months in Tanzania [108].

Data from [101,103] show that there has been a significant increase in solar use in Tanzania between 2012 and 2016, especially in rural areas (Figure 3.1). Meanwhile, the use of kerosene has dropped steeply and the use of disposable or rechargeable battery powered lanterns and flashlights has increased significantly. It is unclear if solar rechargeable lanterns are included in this category. Regardless, it is evident that the solar market is growing in Tanzania, and we aim to understand why. Through our research, we intend to uncover ways to accelerate growth of solar in Tanzania and beyond.

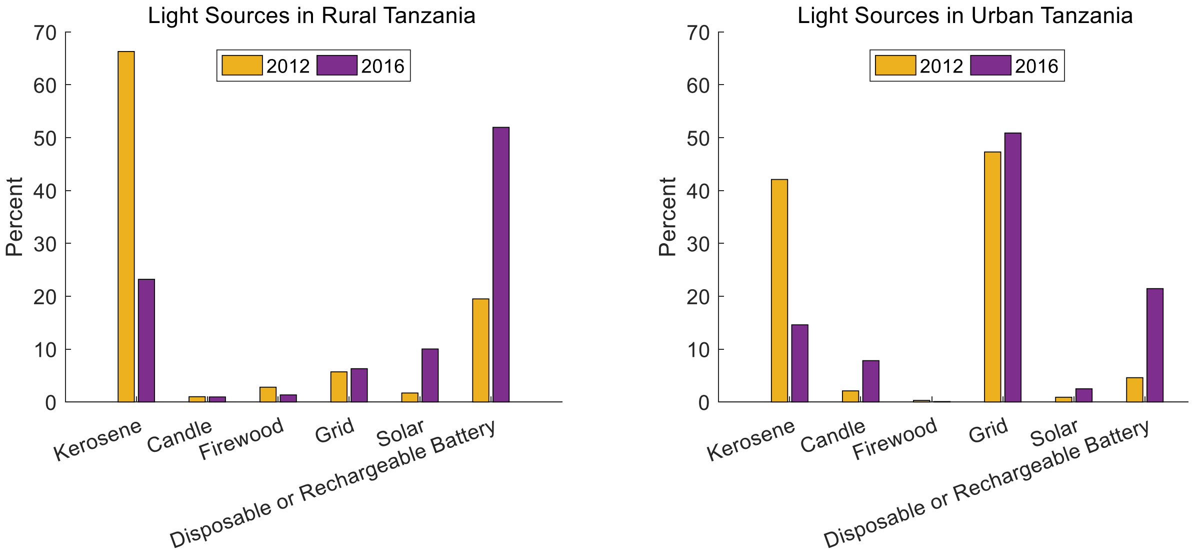


Figure 3.1: Sources of light in rural (left) and urban (right) Tanzania, from the 2012 Housing and Population Census and the 2016 Energy Access Situation Survey[2] [101,103].

The main objective of this paper is to shed light on the drivers and barriers to solar adoption in Tanzania. We focus on households' decisions to purchase solar lights, using the "Four A's": awareness, attraction[3], affordability, and availability, which provide a framework for understanding the adopter perspective [43]. In the next section, we define the Four A's framework in more detail, with references to relevant literature. Next, we describe our data collection methods, survey instrument, and analysis methods. Then we provide the results of our research, and in the discussion section we derive additional insight from the results by applying the Four A's framework.

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[2] The published results of the 2016 survey totaled more than 100%, because more than one source could be reported. For this figure, we normalized the 2016 results to total 100% so that they could be compared more directly to the 2012 results—which only reported the primary source, and totaled 100%

[3] In the original framework defined by Anderson and Markides, the second A stands for "acceptability." We modify this to "attraction" in this context because we think it better captures the concept of what draws consumers and drives demand.

3.3 Framework

Anderson and Markides developed the Four A's framework because they found that much of what drives successful business innovation in the Western world does not apply in emerging economies. Instead of finding new customers, developing new products, or employing new business models, innovators in emerging economies need to establish market basics to serve the underserved. This can include sourcing appropriate products that are **affordable** and **attractive**, creating distribution channels to ensure product **availability**, and generating demand among customers who lack product **awareness** [43]. Because the Four A's framework succinctly captures the fundamental elements of business success in emerging economies, we used it to guide our assessment of the state of the solar market in Tanzania.

Having **awareness** of a technology is an important prerequisite to adoption. Despite this importance, little is being done to raise awareness, in part due to the limited marketing capacity of retailers and the associated expense [17]. As such, there is a lack of awareness and knowledge, which negatively affects uptake of solar products [15,52]. Awareness of benefits is especially critical [15,17,21].

Solar products must be **attractive** to potential customers in order to create demand for them, allowing the solar market to grow and be successful [17,51]. To generate attraction, solar products should be compatible with the needs, desires, and culture of potential adopters, who must see the advantage of these products relative to their current sources or other alternatives [15,23]. Consumers desire products which have bright light, are reliable, have adequate run-time, and can charge a mobile phone [17,60–62]. Another feature that can enhance attraction is the ability to power a TV [50].

Affordability is seen as one of the most important factors in the diffusion of solar products in emerging markets [50,66,71]. Researchers have shown that uptake of solar has been higher among wealthier households [47,54,63]. Although solar products are becoming increasingly cost-effective, affordability is still limited by the ability to pay upfront costs, and limited access to credit or flexible payment options [23,50,67].

Limited **availability** of solar products in emerging economies hinders the development of a sustainable solar market, and vice versa. In addition to being limited by market demand, availability is impeded by poor transportation infrastructure and distribution networks, and low population densities in rural areas [17,50,67]. Availability is higher in urban areas, but there are conflicting results on whether distance from urban areas is a determinant of solar uptake [51,53,54,78]. At the national level, policies such as import duties on solar products can affect the availability and affordability of these technologies [109,110].

While it is helpful to conceptualize each of the Four A's separately, there are also important factors and processes that cut across and link these different drivers. Two examples are product quality and peer networks. To the extent that the solar products that are available in emerging markets are low quality [17,49], these products have the potential to decrease attraction and thereby hinder the development of solar markets over time. Even low-quality LED flashlights have the potential to spoil the market for solar lighting products, since they also use LEDs. Thus, it is imperative that high-quality solar products are available, and that potential buyers are aware of quality issues and can positively identify high-quality products [61].

Similarly, peer networks may have a role to play in increasing awareness of and attraction to solar products. People most often learn about solar technology from family, friends, neighbors, and observations of nearby systems [78,79]. Previous studies have observed geographic clustering of solar and explored how this clustering may affect awareness and attraction [53,54], but further research needs to be done to establish causal links between peer influence and solar adoption.

3.4 Methods

In order to identify household-level drivers and barriers of solar adoption in Tanzania, we carried out surveys of solar users and non-users in the Arusha and Kilimanjaro regions. We did not develop our survey instrument using the Four A's, but we did use this framework when interpreting the results. The Four A's lens was useful for developing a generalizable and actionable understanding of which factors may be contributing to increased solar use in Tanzania, and which may be constricting growth.

3.4.1 Location and Sample Selection

This research took place in Tanzania, a coastal country in East Africa with an estimated population of 54 million (2017), and land area of 885,800 km^2 (slightly more than double that of California). More specifically, the research took place in the Arusha and Kilimanjaro regions (Figure 3.2), which border Kenya to the North and had a population of 1.69 million and 1.64 million respectively, as of the 2012 census [111,112].

Within the Arusha region is the city of Arusha, which had a population of about 416,000 (2012). Within the Kilimanjaro region is the city of Moshi, which had a population of 184,000 (2012). The two cities are about 80 km apart and connected by a two-lane road that continues 550 km to the southeast to Dar es Salaam – the economic capital of Tanzania and the most populous city in East Africa at an estimated 5.1 million people (2015) [111,112]. For more background on Tanzania, including grid network maps and electricity generation fuel makeup, see Appendix 6.1.1.

The boundary of our study was a 60 km radius of both the city of Arusha and Moshi, and excluded the Arusha city and Moshi municipal districts. These areas were of interest because two international solar retailers are active here, Mobisol and Mpower (Off-Grid Electric), in addition to a number of local retailers. Thus, our results shed light on solar adoption in a context where active market development is ongoing.

In an attempt to maximize the representativeness of our sample population, while maintaining a feasible study design, a random cluster sample was used. Initial randomization occurred at the ward level, since village or census data were not available. There were 45 wards within the study area in the Arusha Region, and there were 101 wards within the study area in the

Kilimanjaro Region. We randomly selected nine wards from each region, but we were only able to carry out surveys in eight wards per region[4], which are identified in Figure 3.2. Two villages were randomly selected within each ward, and 10 surveys were carried out in each village.

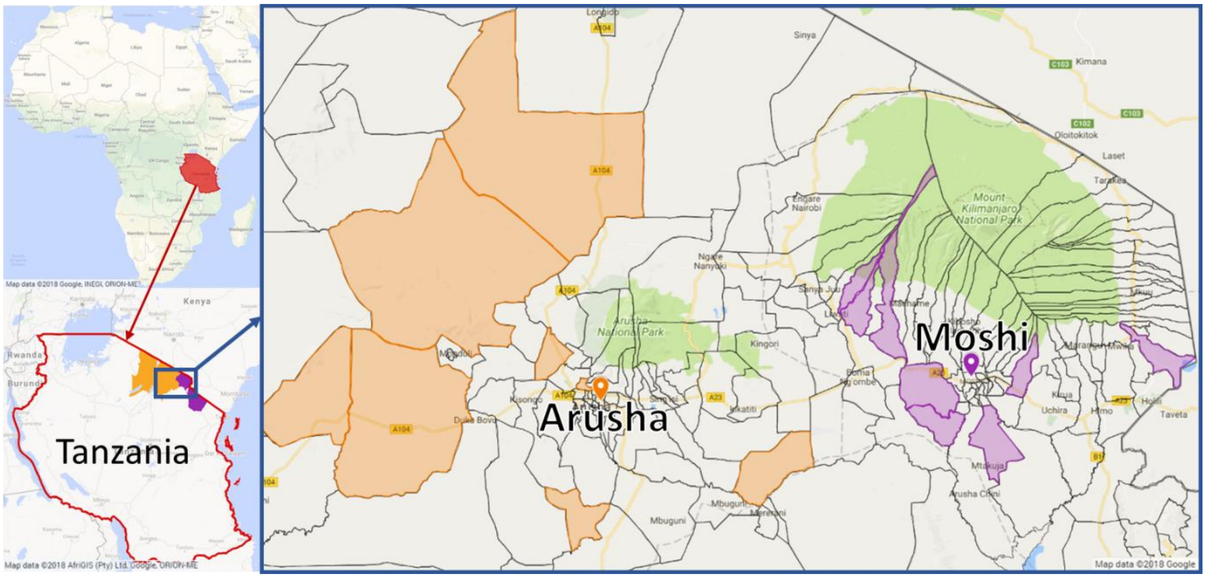

Figure 3.2: Map of study area with sampled wards in the Arusha region in orange and sampled wards in the Kilimanjaro region in purple.

Since census data were not available, the village chair was asked to generate a list of households from memory. Creating the list proved to be a somewhat difficult task, so we deemed 30 households to be sufficient, from which 12 were randomly selected for survey recruitment. The village chairs were aware that solar was the focus of our study, but we instructed them not to consider households' energy sources when generating their lists. However, we acknowledge that the set of households easily recalled by the village chair may differ systematically from the full population of households in a village, such that our survey sample is not necessarily representative of the latter. This is a limitation of our study, which we discuss further when interpreting our results.

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[4] We were unable to contact three wards in the Arusha region, so an additional three wards were randomly sampled.

3.4.2 Survey

We carried out a mixed-methods survey over the course of three weeks in January and February of 2016. Surveys were conducted in Swahili by two local enumerators. The survey consisted of questions on demographics, current light sources, knowledge of solar topics, opinions of solar, perceived product quality, peer networks related to solar, income, and assets. These survey topics are summarized below, and the complete list of questions are shown in the supplemental material.

The primary respondents for these surveys were heads of household, regardless of gender. In instances where only one head of a household was available, or one was more immediately available than the other, we surveyed that person. When both heads of a household were present, we allowed them to complete the survey together or choose who would respond. About 12% of those surveyed did not identify themselves as a head of household, so these responses were not included in the analyses described below.

Participants were asked what their primary and secondary light sources were, then were asked follow-up questions specific to their primary light source, including their lighting/energy expenditures and level of satisfaction. If they used solar as a primary or secondary source, they were asked if they used a solar home system (SHS) or solar lantern, then they were asked questions specific to these technologies. Example SHS questions included size, brand, year of purchase, and items powered. Example solar lantern questions included cost, number owned, and number that have broken. Solar users were also asked open-ended questions, including *why did you choose to use solar?*, and *who was most influential in your decision to use solar?*. Non-users were asked open-ended questions, including *why don't you use solar?*, and *what have you heard about solar?*.

There were 11 knowledge question statements on the survey, including *I know about the different types of solar products,* and *I know the price of a solar lantern*. Response levels were *completely agree*, *agree*, or *disagree/don't know.* Using a five-point Likert scale proved problematic, as our translation for the *neutral* level was confused with the *don't know*[5] (*disagree*) level in the context of knowledge questions, so the *neutral*, *disagree*, and *completely disagree* levels were combined. There were three questions on the desire for more knowledge, including the *type of information desired*.

There were 14 opinion question statements on the survey, including *solar products save me money*, *solar products improve health*, and *solar products are sold nearby*. Response levels were *completely agree*, *agree, neutral, disagree, and completely disagree.* Because there were so few *disagree* and *completely disagree* responses for opinion questions, these levels were combined with the *neutral* level for analysis[6].

There were eight product quality questions included on the survey, including *what is the expected lifetime of a flashlight/solar lantern/SHS?*, and *I can identify product quality*. The eight peer network questions included on the survey included, *how many of your family members use solar?*, and *what are their opinions?* Additionally, respondents were asked basic questions about their demographics, income, and assets.

3.4.3 Data Analysis

We started by computing descriptive statistics (frequencies, means, etc.) for key variables. We examined bivariate relationships between solar ownership and several other variables, as well as other bivariate relationships, like education and grid use, and gender and household decision making. We used chi-square and Pearson correlation coefficients to test for significance in bivariate relationships, and p-values for these tests are show in the figures in section 3.5.3. For multivariate analyses, we used logistic regression to assess the relationship between solar use (binary outcome) and the predictors (survey question responses). To account for within region

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[5] Our Swahili translation for the neutral response level was somewhat synonymous with "don't know." This became an issue, but only for the knowledge questions because neutral and disagree responses both meant "don't know" in the context of these questions. The neutral level did not cause issues for the opinion and other question categories, e.g. *solar products save money?* -> don't know==neutral.

[6] For other multiple-choice survey questions with response levels selected by less than 10% of respondents, those levels were combined with the nearest response level.

(Arusha, Kilimanjaro) correlation, we used a generalized linear mixed model with a logit link function, also known as a mixed effects logistic regression. The equation for this model for individual i in group j with one independent variable is:

$$logit(p_{ij}) = \beta_{0j} + \beta_{1j}x_{1ij} + \varepsilon_{ij} \qquad (1)$$

where β_{0j} and β_{1j} are random coefficents which are a function of group j. The group-level coefficients are given as:

$$\beta_{0j} = \beta_0 + u_{0j} \text{ and } \beta_{1j} = \beta_1 + u_{1j} \qquad (2\ \&\ 3)$$

where β_0 and β_1 are the mean intercept and coefficient, and u_{0j} and u_{1j} are the group level errors, i.e. the random effects. Thus, this model accounts for both the within group variance and the between group variance simultaneously. Substituting equations 4 and 5 into equation 3, rearranging, and representing in matrix form yields:

$$logit(\vec{p}) = \boldsymbol{X}\vec{\beta} + \boldsymbol{Z}\vec{u} + \vec{\varepsilon} \qquad (4)$$

where $\boldsymbol{X}$ is a matrix of independent/predictor variables, $\vec{\beta}$ is a vector of fixed effects, $\vec{u}$ is a vector of random effects, $\boldsymbol{Z}$ is the random effects design matrix, and $\vec{\varepsilon}$ is a vector of error terms [113].

Assessing household wealth with a single question about income can be unreliable in rural areas where many households practice subsistence agriculture. We used principal components analysis (PCA) to generate a relative socio-economic status index from household assets and other wealth related questions, following the methodology outlined in [114]. We used the first principle component[7] from the PCA to place households into quartiles which represent four levels

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[7] Although higher order principle components can be included, we used the first principle component because it is assumed to be a measure of economic status [114], and because the component weights from the first principle component did not result in a wealth indicator that favored one region over the other, while the second principle component resulted in the Kilimanjaro region appearing much more wealthy. The primary asset in the Arusha region was cows, while goats and chickens were far more prevalent in the Kilimanjaro region due to cultural and geographic differences. The second principle component put more weight on assets that were more common in the Kilimanjaro region, while the first principle component weighted the respective assets more evenly.

of wealth (first quartile: least poor, fourth quartile: most poor). Six variables were included in the PCA: weekly income, number of days to save ~7 USD, and the number of cows, goats, chickens, and acres of land.

3.4.4 Model Specification

We used the Four A’s to guide our selection of independent variables for inclusion in the regression analysis. We wanted to include one or two predictors from each survey category, so that our model would not overfit or be too complex to converge. The primary considerations for choosing a predictor were its perceived importance in the context of the literature review, response rates, missing values, and the distribution of responses – e.g. if 90% of the responses to a question were *completely agree*, then that question was not included in the model. The selected variables are shown in Table 3.1.

Table 3.1: Questions and question statements included in the regression analysis.

Category and Question	**Potentially Relevant A’s**
Knowledge	
I know the benefits of solar products	Awareness, Attraction
Opinions	
I will purchase a(nother) solar product in the future	Attraction
Solar products are sold nearby	Awareness, Availability
Product Quality	
I can identify between high quality and low quality solar lanterns	Awareness
There are high-quality solar lanterns available at the market	Awareness, Availability
Peer Networks	
How many of your family members use solar products?	Awareness, Attraction
How many of your family members have told you about their solar product(s) breaking?	Awareness, Attraction
Wealth	
Wealth indicator (by quartile)	Affordability
Other	
Distance from village to the nearest major city[8]	Availability
Education level	Awareness
Household size	Affordability

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[8] Straight line distances were calculated from each village office to the nearest major city (i.e. Arusha or Moshi) using GPS coordinates.

Variables found to be significant in the full model were included in a reduced model to see how significance and effect sizes changed when fewer variables were included in the model. Since fewer variables were included in the reduced model, fewer respondents were excluded due to blank responses[9]. This allowed us to check the robustness of our results as the useable sample size increased.

3.5 Results

3.5.1 Descriptive Statistics

Table 3.2 shows the characteristics of our sample: age, household size, income regularity, house wall material, house roof material, and ownership of cellphones, cars and motorcycles. Our measured household size of 6.0 is higher than the Tanzania average of 4.7 (2012), possibly because we were in rural areas where households tend to be bigger. This same explanation could apply to education levels, which we found to be lower than those of the 2012 census that showed 81.7% completed primary school. Household wall and roof materials were more comparable to census values specific to Arusha and Kilimanjaro, see the supplemental materials for a table with this comparison [115]. We expect some deviation from census values, since we do not have a representative sample.

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[9] Respondents with a blank response for any question included in the model were removed from the analysis.

Table 3.2: Descriptive statistics.

Gender	45.1% Female	54.3% Male
Age	Mean: 43.4	Range: 20-90
Household Size	Mean: 6.0	Range: 1-26
Income Regularity	95.7% Variable	2.2% Wage/Regular
Education		
Did not complete primary	17.6%	
Completed primary school	57.7%	
Completed secondary school	14.2%	
University or trade school	3.7%	
Blank	6.2%	
House Wall Material:		
Brick	53.7%	
Mud	30.9%	
Other	2.4%	
Blank	12.7%	
House Roof Material:		
Metal	83.3%	
Grass	4.6%	
Blank	12%	
Households with one or more:		
Cellphones	98%	94% (blanks as zero)
Cars	3.7%	3.4% (blanks as zero)
Motorcycles	17%	16% (blanks as zero)

3.5.2 Solar Use and Other Light Sources

The breakdown of primary light sources by gender and by region is shown in Figure 3.3. We found that 46.6% of our sample used a solar product for their primary source of light. There was not a significant difference in light source by gender of the respondent ($p = 0.49$), but there was a significant difference by region ($p < 0.001$), with 60% of respondents in Arusha and 33% of respondents in Kilimanjaro using solar. When accounting for solar used as a backup source of light, a total of 56.5% of respondents used solar technology.

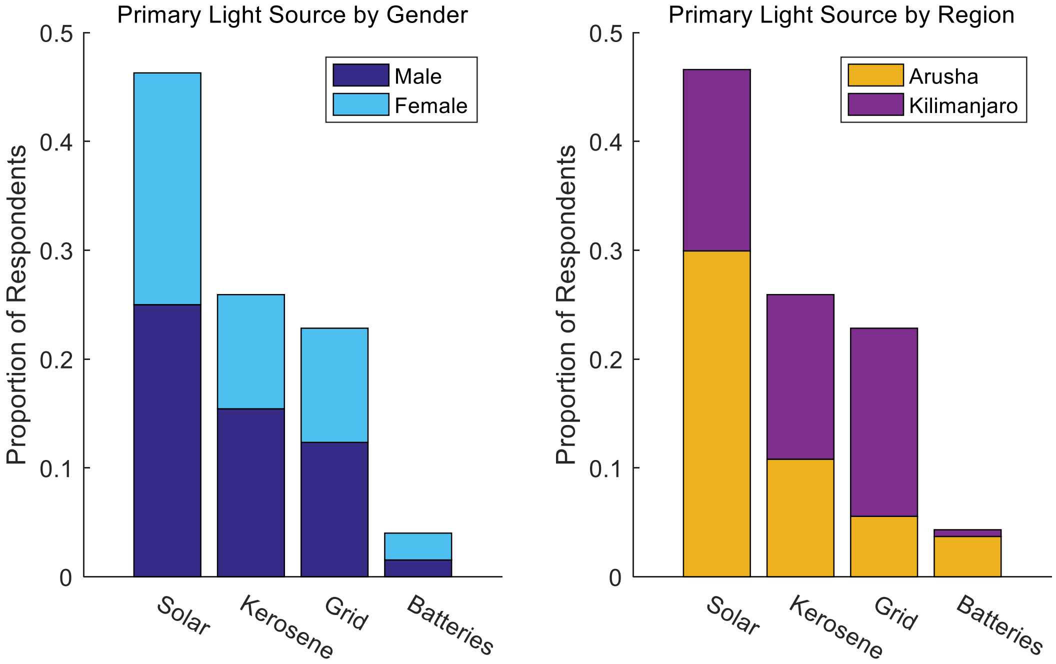


Figure 3.3: Primary light sources by gender (left) and region (right).

The next most used primary light source among our respondents was kerosene, and grid use was nearly as prevalent, with very few respondents using batteries. If we assume the grid was unavailable in villages where we surveyed zero gird users, then three-fourths of the villages had grid availability in at least part of the village. The high level of grid availability is likely due to the research area’s proximity to major cities.

Figure 3.4 shows the types of solar products used and the uses for SHS. Nearly two-thirds of solar users were using a SHS, and about one-third were using standalone solar lanterns. The median SHS size was 60W, and 92% reported using their system for cell phone charging, 55% were powering a radio, and 29% were powering a TV, with virtually all using their system for light.

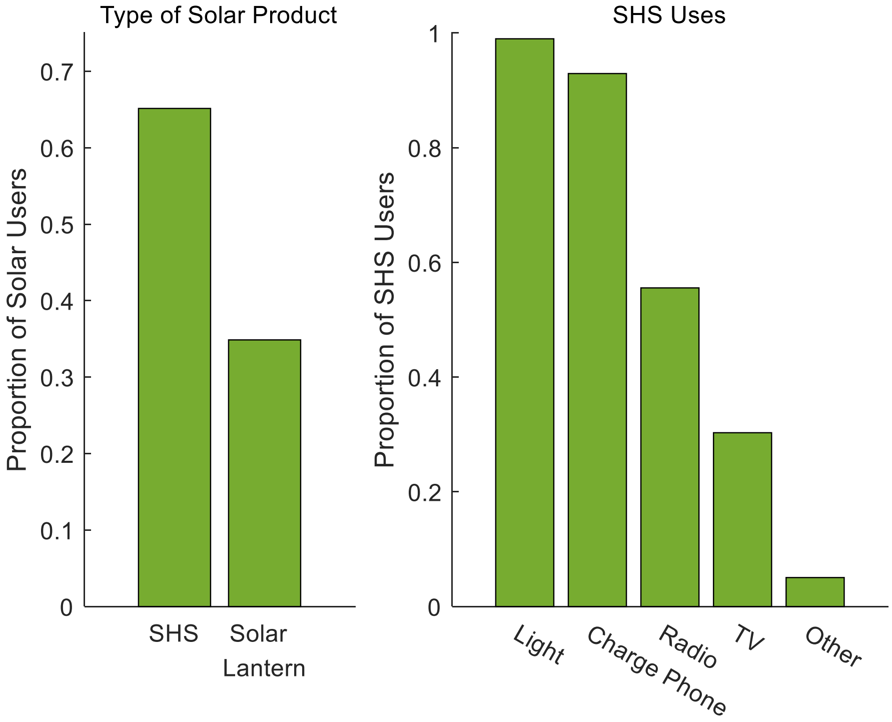


Figure 3.4: Types of solar products (left) and SHS uses (right).

Solar lantern users had 1.8 lamps on average, and about one-third had a lantern break in the past. Lantern users spent an average of 7.53 USD to purchase their products. In comparison, kerosene users spent an average of 6.82 USD per month on kerosene. Respondents who used batteries as their primary light source spent an average of 3.60 USD per month. If a solar lantern displaces 50% of kerosene or battery expenditures, it would pay for itself in a little over two months or four months, respectively.

The map in Figure 3.5 shows village level uptake of solar products, where the different colored markers represent the proportion of solar use among households surveyed in each village. There is not a visually perceptible relationship, either positive or negative, between solar use and distance from the village to a major city (i.e. Arusha or Moshi), or distance to a major road.

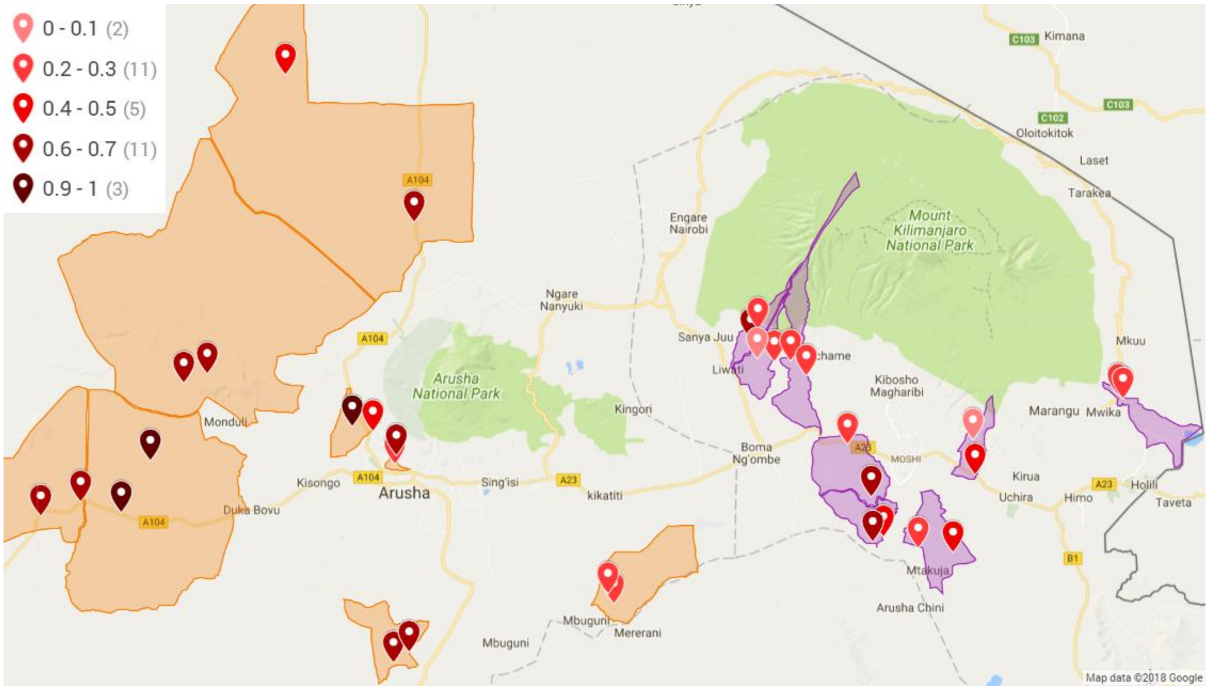


Figure 3.5: Village markers where darker red corresponds with a higher proportion of solar users surveyed. The number in parenthesis in the legend indicates the number of villages with that proportion of solar use.

3.5.3 Select Independent Variables

Knowledge

The overall level of knowledge of solar topics was generally low for the 11 knowledge questions. Users always had higher levels of self-reported knowledge of solar topics relative to non-users, and this difference was statistically significant for all 11 questions. However, a considerable proportion of users still lacked knowledge. An example of this is, *I know where to buy solar products* (Figure 3.6); about two-thirds of respondents did not know where to buy a solar product, and almost one-third of users also did not know—despite having purchased one.

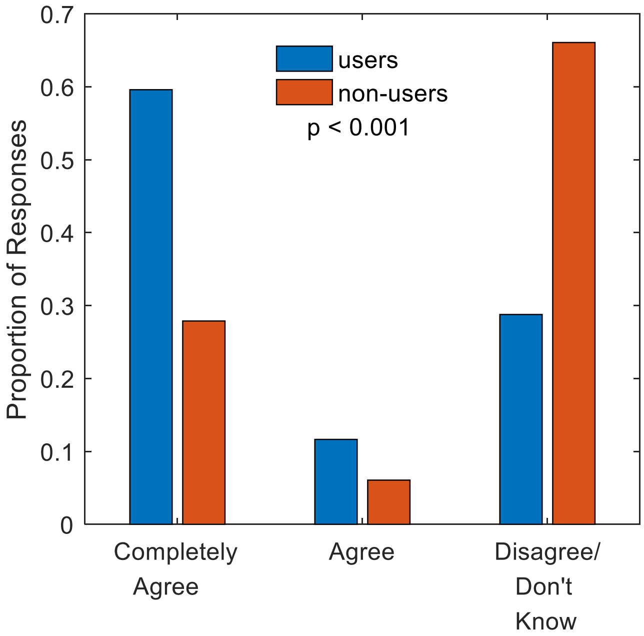


Figure 3.6: User and non-user responses to the statement, *I know where to buy solar products.*

Another measure of knowledge is, *I know the benefits of solar products,* as shown in Figure 3.7*.* Most users said that they know the benefits of solar products, and very few said they do not know the benefits. This question had the highest number of completely agree responses for both users and non-users, among the knowledge measures, though almost half of non-users were still neutral or disagreed.

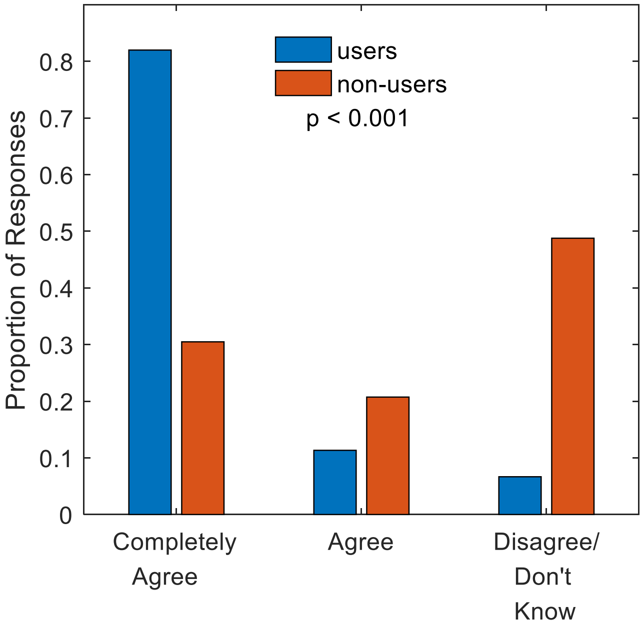


Figure 3.7: User and non-user responses to the statement, *I know the benefits of solar products.*

Another knowledge question statement was, *I know the price of a solar lantern*, which was followed by *what is the cost of a solar lantern?*, if respondents agreed to the former. The average response to the latter was 6.25 USD. We believe some respondents thought we were asking about DC LED lightbulbs often used in SHS, so if we exclude responses below 2 USD, the average was about 9 USD. These values are comparable to the average lantern purchase price in our sample (7.53 USD), and the approximate price of an entry-level d.Light solar lantern in Arusha or Moshi (7 USD). However, more than two-thirds of non-users said they did not know the price of a solar lantern. Without this knowledge, it would be difficult to be aware of the financial benefits relative to kerosene.

I know how solar energy works and *I know how to use solar products* had a high number of agree responses for users, relative to some of the other knowledge questions. For measures such as these, users may have simply gained knowledge through the purchase and ownership of a solar product; we cannot conclude that higher levels of knowledge lead to higher levels of uptake. However, 88.6% of respondents (89.4% of users and 87.8% of non-users) *completely* *agreed* that they would like more information about solar technology. The primary topics of interest were the benefits of solar products and how to identify high-quality products.

Opinions

Overall opinions were high among both users and non-users, though users generally had higher opinions compared to non-users, and this difference was statistically significant for 13 of the 14 opinion measures. An example of this is, *solar products (would) save me money* (Figure 3.8); more than 90% of users and more than two-thirds of non-users completely agreed. This would suggest that most non-users should understand the financial benefits of solar, but it would be difficult to accurately gauge financial benefits for the large proportion of non-users who did not know the price of a solar lantern. Many of the other opinion questions have similar response patterns, including: *solar products increase study time*, *solar products have bright light*, and *solar products are good for health*.

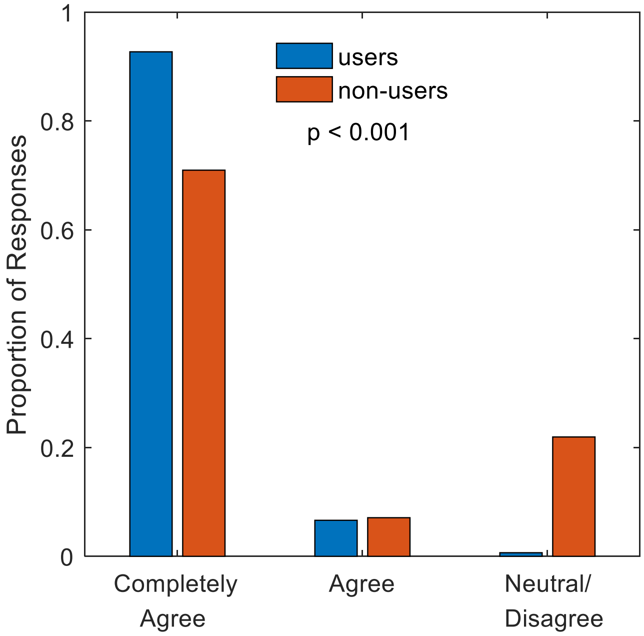


Figure 3.8: User and non-user responses to the statement, *solar products (would) save me money.*

Another opinion question statement is, *solar products are sold nearby,* as shown in Figure 3.9. About one-quarter of users and one-half of non-users were neutral or disagreed. This question had the highest neutral/negative response rate among the opinion measures. The high number of negative responses may be a result of actual proximity to available products, or a lack of awareness of nearby purchase options. Additionally, the significant difference in responses between users and non-users may be a result of users being closer to solar retailers.

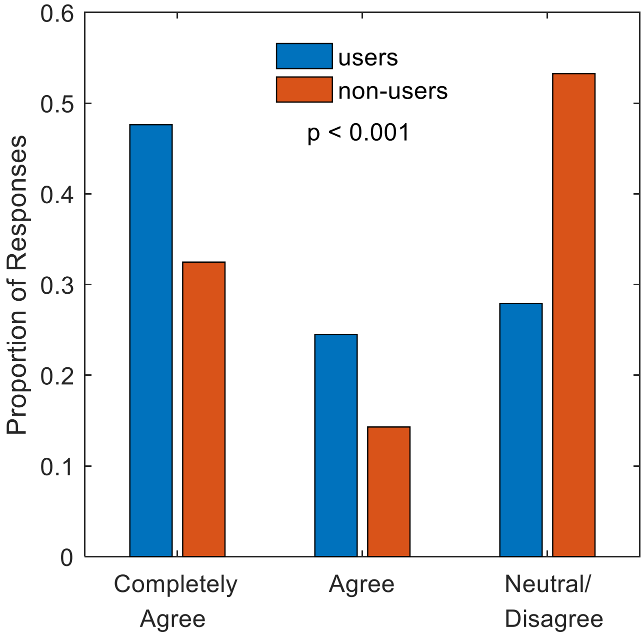


Figure 3.9: User and non-user responses to the statement, *solar products are sold nearby.*

Another opinion measure is, *I will buy a(nother) solar product in the future.* Nearly 90% of solar users agreed, which demonstrates a high level of satisfaction with their current products. More than two-thirds of non-users also agreed, indicating a high level of attraction for solar products. Responses to this question were not significantly different for users and non-users. Because of the strong positive responses to this question, and the overall high opinions of solar, it appears that attraction has been a driver of solar uptake in this area of Tanzania. It is likely that non-users have faced other barriers, which attraction alone cannot overcome.

Product Quality

Participants were asked how long they expected flashlights, solar lanterns, and SHS to last, in order to gauge their awareness of product longevity and potential quality issues. The median reported life expectancy was four weeks for battery powered flashlights, two years for solar lanterns, and five years for SHS. The difference in expected life among users and non-users was similar for flashlights (p = 0.76), as well as solar lanterns (p = 0.57). However, there was a statistically significant difference in mean life expectancy of SHS for solar users (8.9 years) compared to non-users (5.4 years) (p = 0.006). The two-year life expectancy of a solar lantern is reasonable, as it corresponds with the length of many warranties on such products. It is possible that market spoiling has been mitigated in part by increased awareness of warranty periods and expected longevity.

About two thirds of respondents expect battery powered flashlights to last less than one month, which is comparable to research findings in Kenya, where flashlight users reported an average lifespan of three and a half weeks [116]. However, we did not find evidence of flashlight-related market spoiling in our study, since their short life expectancy does not appear to negatively impact the expected life of solar products. It is possible that the commonality of LED technology was not enough for consumers to associate low quality flashlights with solar products. However, both users and non-users primarily agreed with the question statement, *there are low-quality products available*, about one-third of solar lantern users reported a prior product failure, and very few could identify high quality products (Figure 3.10). Thus, product quality and market spoiling are still concerns.

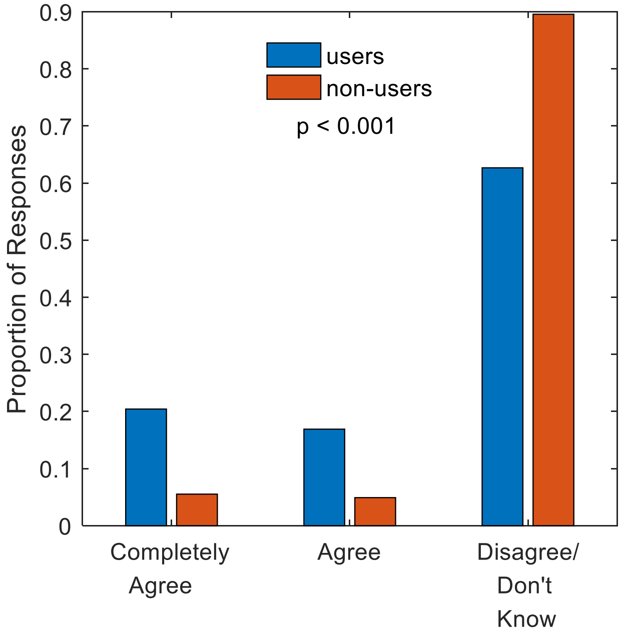


Figure 3.10: User and non-user responses to the statement, *I know how to identify high-quality products.*

Peer Networks

Almost all users and non-users reported that their family, friends and neighbors had high opinions of solar (Figure 3.11), though these peer opinions were slightly higher among users, and this difference was statistically significant. Users *and non-users* also had a high proportion of respondents who *have heard convincing reasons to use solar*. Additionally, very few users or non-users reported hearing about products breaking from their peers. These results imply that peer influence alone cannot drive adoption, at least in the presence of other barriers. However, peers may still be an important means of increasing awareness.

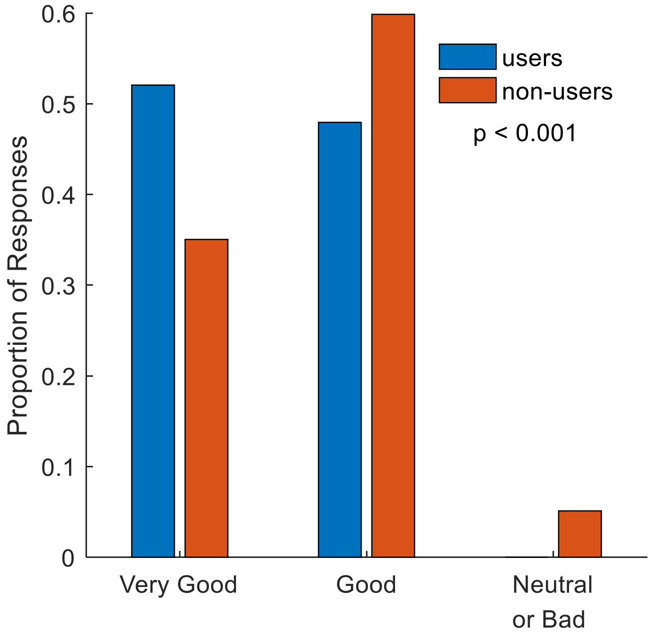


Figure 3.11: User and non-user responses to the question, *what are your family members' opinions of solar?*

Wealth

To assess households' ability to afford solar products, we examined measures of households' financial assets and purchasing power. Figure 3.12 shows the the distributions of responses to questions that assess households' income, savings, and credit access: their usual weekly income, the amount of money they could potentially save in a week, and the amount of money they could potentially borrow in a week. Weekly income was slightly higher for users, and possible weekly savings was slightly higher for non-users, but these differences were not statistically significant. Thus, purchasing power was quite similar for users and non-users. The mean potential weekly savings for users (7.18 USD) and non-users (8.55 USD) was comparable to the price of a solar lantern (approx. 7 USD).

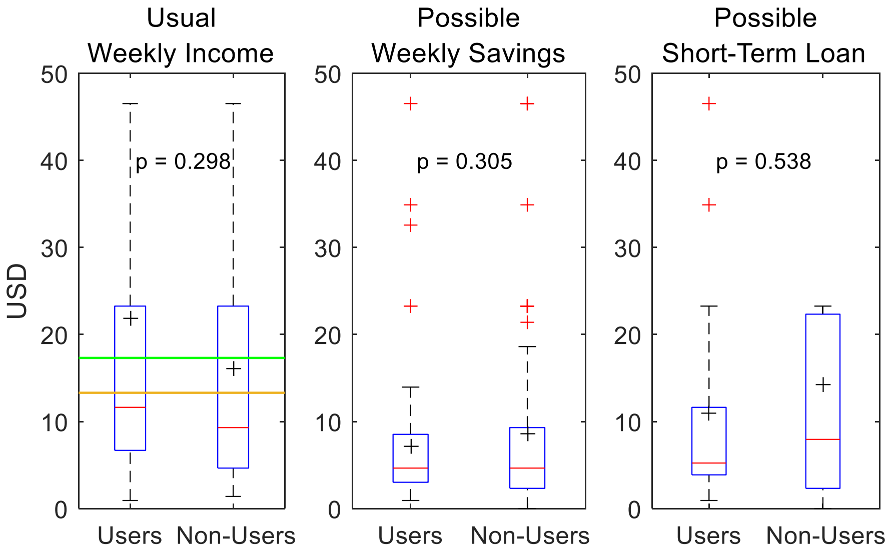


Figure 3.12: Reported weekly income (left), where the red line represents the median, the + represents the mean, the green line represents the 2015 GNI/capita/week [117], and the orange line represents the poverty line (1.90 USD/day); possible weekly savings (middle), and possible short-term loan (right).

We used PCA to develop a relative wealth index using household assets. The first principle component explains 25% of the variance in assets included in the PCA. The largest weights of the first principle component were acres (0.55), goats (0.48), and cows (0.42). All weights of the first principle component were positive except *number of days to save 15,000 Tsh*. The mean income, number of cows, acres of land, and kerosene expenditures for each of the quartiles is shown in Table 3.3. The decreasing trend of the means of asset variables corresponds with decreasing wealth quartile, which is expected given that the wealth index is comprised of weighted combinations of these variables. However, kerosene expenditures display the opposite trend, with the least wealthy spending the most on kerosene. It is possible that wealthier quartiles are able to spend more on secondary sources like batteries and candles.

Table 3.3: Income, select assets, and kerosene expenditures by wealth quartile

	Wealthiest Quartile	Second Quartile	Third Quartile	Least Wealthy Quartile
Mean Weekly Income (USD)	33.34	15.00	13.56	9.00
Mean Number of Cows	20.2	4.4	2.3	0.8
Mean Acres of Land	6.7	1.9	1.2	0.5
Mean Weekly Kerosene Expenditure (for primary users only, USD)	1.39	1.29	1.46	1.75

The distribution of light sources by wealth quartile (Figure 3.13) shows that kerosene and battery users predominantly fall into the least wealthy quartile, while SHS users predominantly fall into the wealthiest quartile. Uptake of SHS was the lowest in the least wealthy quartile, but solar lanterns were still used by a sizeable proportion of the least wealthy. Note that since we don't have a representative sample, we may not actually capture the poorest of the poor, who may find solar lanterns less obtainable than the poorest people in our sample. The proportion of people in the third quartile using each of the light sources was almost evenly distributed. Thus, the second poorest quarter of our sample does not appear to be financially restricted from the use of solar lanterns or SHS.

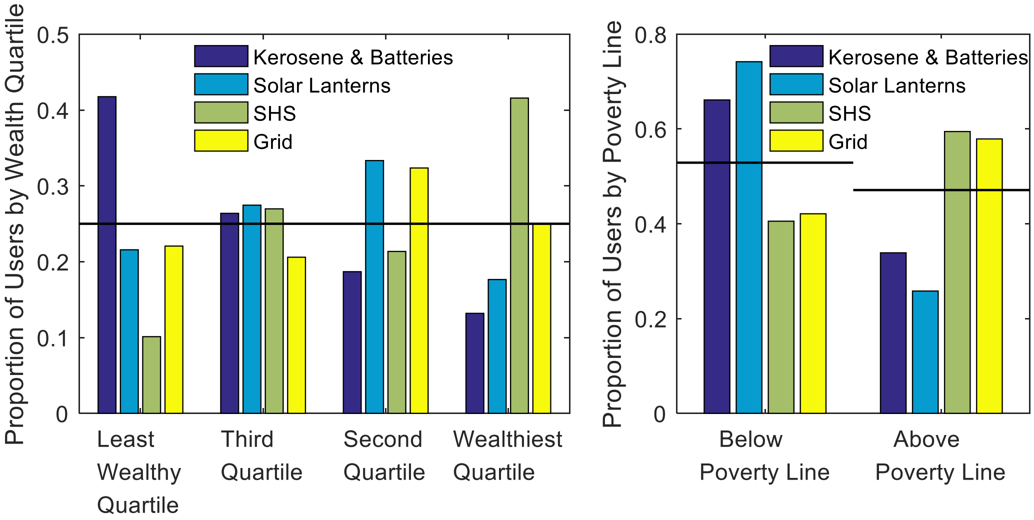


Figure 3.13: Distribution of light sources within each wealth quartile (left), and the distribution of light sources above and below the poverty line (right). The black lines represent the proportion of people in each wealth category (0.25 in each quartile, 0.53 below poverty line and 0.47 above).

To get another perspective on the relationship between wealth and light source, we looked at the proportion of users for each light source who fall above and below the poverty line, in terms of self-reported income (Figure 3.13). Of those who use kerosene and batteries, about two-thirds were below the poverty line and one-third were above. Of those who use solar lanterns, nearly three-fourths live below the poverty line and only one-fourth were above. The median income of solar lantern users was about 7 USD/week, while the median income of kerosene and battery users was about 9 USD/week. This suggests that income below the poverty line was not a barrier to solar lantern adoption, and that the majority of people who can afford to use kerosene and batteries can afford to buy and use solar lanterns.

Of those who use SHS, about 20% more live above the poverty line, and their median income was about 15 USD/week. Of those who use grid power, about 15% more live above the poverty line, and their median income was about 14 USD/week. Thus, it appears that those who can afford grid power can afford a SHS. Tanzanian households which were connected to the grid between 2000 and 2015 paid between 140 and 230 USD on average (median) for their connection [101]. Currently, this amount of money would be sufficient to purchase a modest SHS.

Open-Ended Questions

Solar users were asked an open-ended question about why they chose to use solar products, and 170 respondents gave 313 total reasons. Non-users were asked an open-ended question about why they do not use solar products, and 131 respondents gave 154 total reasons. The responses to these questions were categorized, and these results are shown in Figure 3.14, with users on the left and non-users on the right.

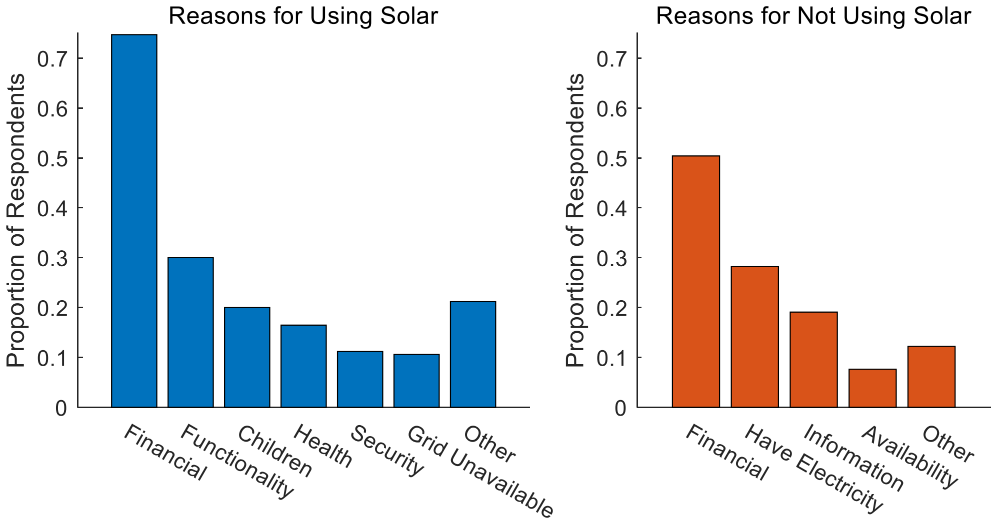


Figure 3.14: Users reasons for using solar, and non-users reasons for not using solar, reported as a proportion of respondents who gave an answer to this question.

Solar users predominantly cited financial reasons, with the bulk of those responses being about the high cost of kerosene. The next most frequently cited reason was related to the functionality of solar products, with most of these responses being about the benefits of light and phone charging. Reasons involving children were the next most common, with nearly all of these being about children studying. Additional reasons for using solar included health, security, and the lack of grid availability.

“Other” reasons for using solar included general positive comments about the technology, general negative remarks about kerosene, environmental reasons, and quality of life. Only two people cited peer influence, “seeing others using it,” making it the one of the least common responses. This may indicate that peer effects were not present, or if peer effects were actually influencing uptake, it may not have been obvious to those being influenced. This is also supported by responses to another open-ended question, *who was most influential in your decision to use solar?*, where 27% of users said *myself*, 17% said *neighbor*, and 17% said *husband/wife*.

Interestingly, financial reasons were the number one response for non-users as well as users. Almost all the financial reasons given by non-users were about having low income or solar being too expensive. This is in line with a study in Kenya, where 94% of households cited affordability as their barrier to solar ownership [47]. As we saw in the previous section, non-users reported income similar to that of users. Thus, the perception of the affordability of solar can be a driver or barrier depending on the perspective of the (potential) adopter. Non-users may have less information on the financial benefits of solar products, or they may not have realistic information on the cost of these products. If non-users had a better understanding of the financial benefits and costs of solar products, they might find these products to be financially favorable—as users do.

The second most common reason given for not using solar was that the household already has electricity. However, the market for solar products for grid users should not be overlooked. Because of the unreliable nature of the grid in Tanzania and elsewhere in Sub-Saharan Africa, many grid users rely on kerosene, battery powered flashlights, and candles when the power goes out. Grid users should be aware of solar products, and their benefits as a backup light source.

Many in this sample were already aware, as nearly one-third of grid users in this sample use solar as a secondary light source, and four respondents use solar power as their primary light source and grid power as their secondary light source.

The third most common reason for not using solar was related to the lack of information or education on solar. The next most common reason was unknown or limited availability, accounting for about 5% of responses. This reinforces findings in Kenya where only 1% of households said they did not use solar because of availability [47]. “Other” reasons included a few general negative statements about solar, that they are waiting for a grid connection, or that they plan to buy a solar product in the future. There were two respondents who reported that they no longer use a solar product because they previously had one that broke. While this is a small number, efforts should still be made to mitigate market spoiling due to low quality solar products.

3.5.4 Model Results

The odds ratios for predictors of solar use from our regression model are shown in Figure 3.15.

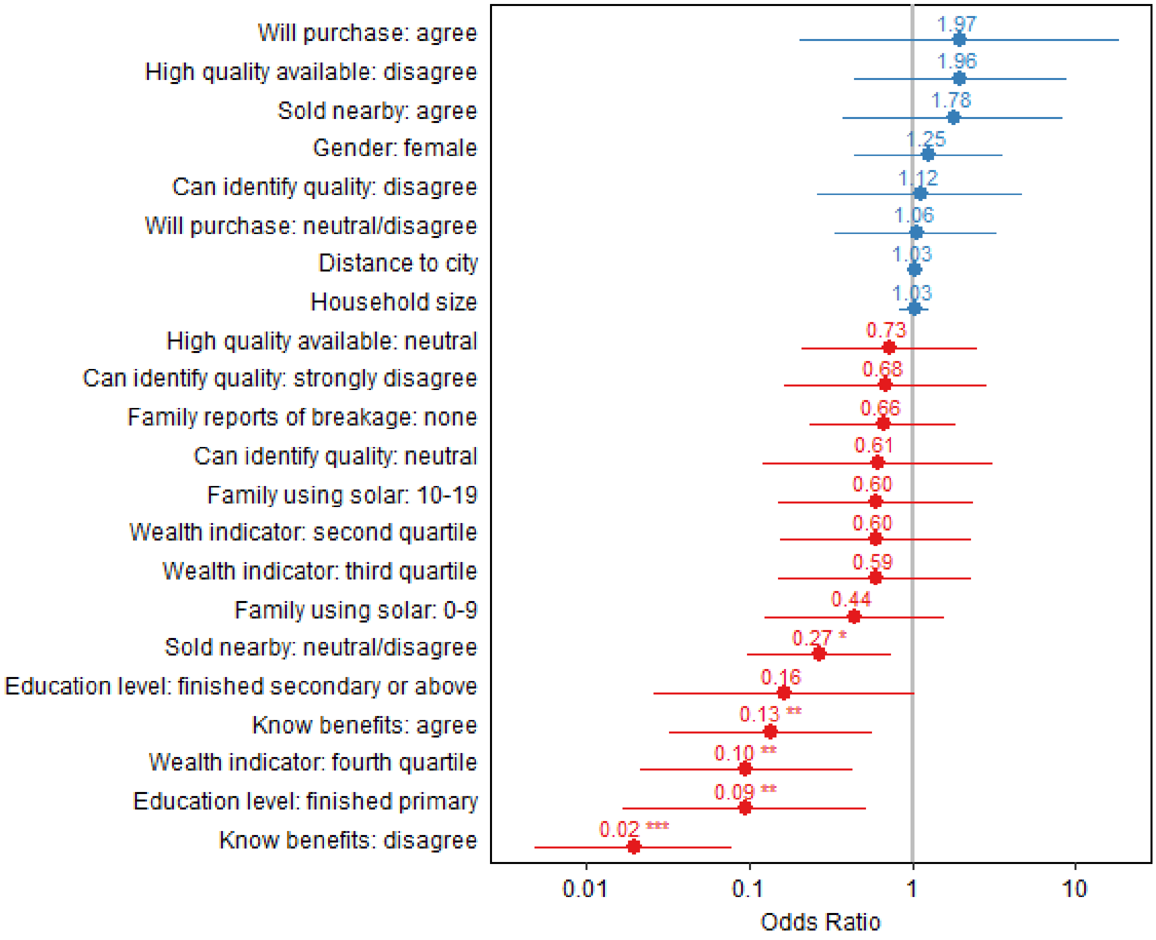


Figure 3.15: Odds Ratios for predictors in the regression model, including 95% confidence intervals. *p≤0.05 ***p≤0.001

Knowledge

The only knowledge question statement included in the model was, *I know the benefits of solar products*, and the distribution of responses to this statement are shown in Figure 3.7. The *agree* and *disagree/don't know* responses to this statement were significantly and negatively associated with solar use, in comparison to the reference response of *completely agree*. The odds of solar use among respondents that said they know the benefits of solar (*completely agree)* was about 50 times higher compared to those that said they do not know the benefits (*disagree)*, when controlling for other predictors. This finding suggests that there is greater attraction to solar products among people who are aware of the benefits. This reinforces existing literature which places an emphasis on increasing knowledge of the benefits of solar. It is also possible that this is simply the result of solar users gaining knowledge of the benefits after purchasing a solar product.

Opinions

The first opinion question statement included was *solar products are sold nearby*, and the distribution of responses to this statement are shown in Figure 3.9. A neutral/disagree response to this question was significantly and negatively associated with solar use, in comparison to the reference response of *completely agree*. The odds of solar use among respondents that said solar products are sold nearby (*completely agree)* was about four times higher compared to those that said solar products are not sold nearby (*neutral/disagree)*, when controlling for other predictors. The second opinion question statement included in the model was *I will purchase a(nother) solar product in the future*. The self-reported likelihood of making a future solar purchase was not significantly correlated with solar use once we control for other covariates.

Product Quality

The first product quality question statement included was, *I can identify between high quality and low quality solar lanterns*. Although more users agreed to this ability, we did not find evidence of a relationship between solar use and being able to identify solar product quality, once we controlled for other covariates. Though the ability to identify quality is seen as important in the literature, it may not be a driver of solar adoption. The second product quality question statement included in the model was, *there are high-quality solar lanterns available at the market.* Although more users agreed to this, we did not find evidence of a relationship between solar use and the perception of high-quality products being available once we controlled for other covariates.

Peer Networks

The first peer network question included in the model was *how many of your family members use solar products?* More users reported knowing more than 20 family members who use solar, while more non-users reported knowing four or fewer family members who use solar, but this could be attributed to a number of causes that may result from geographic or other underlying factors. In the model, we did not find evidence of a relationship between solar use and solar-related peer network size once we controlled for other covariates.

The second peer network question included in the model was *how many of your family members have told you about their solar product(s) breaking*. Around one-quarter of both users and non-users said that their family members have told them about their solar products breaking. This could be a result of predominantly high-quality solar products being purchased, or because negative information is less likely to pass through the peer network, possibly because of cultural norms in the survey location. This predictor was not significant in the model, thus we did not find evidence of a relationship between solar use and negative information about quality passing through peer networks once we controlled for other covariates.

Wealth

The only wealth variable included in the model was the PCA derived wealth indicator. The least wealthy quartile was significantly and negatively associated with solar use, relative to the wealthiest quartile reference level. The odds of solar use among respondents in the wealthiest quartile was about five times higher compared to those in the least wealthy quartile, when controlling for other predictors. Other levels for this variable were not significant, which reinforces that affordability was primarily a barrier for the least wealthy households in our sample.

Other

The distance to the nearest major city was the first “other” variable included in the model, and it was not significant. This inconclusive result, and conflicting results from previous studies may indicate that rural areas do not necessarily have lower solar uptake. This position is supported by research in Sri Lanka, which showed that availability was initially higher in population centers with solar distribution hubs, but as time went on availability in rural villages increased, and uptake was ultimately higher in these areas [65]. Need and demand in remote areas may be great enough to overcome potential issues with availability in these areas. In the case of our research, it is also possible that our study area did not extend far enough from the cities to see a drop-off in availability and uptake. Additionally, we do not know how availability may have expanded and changed in this area over time.

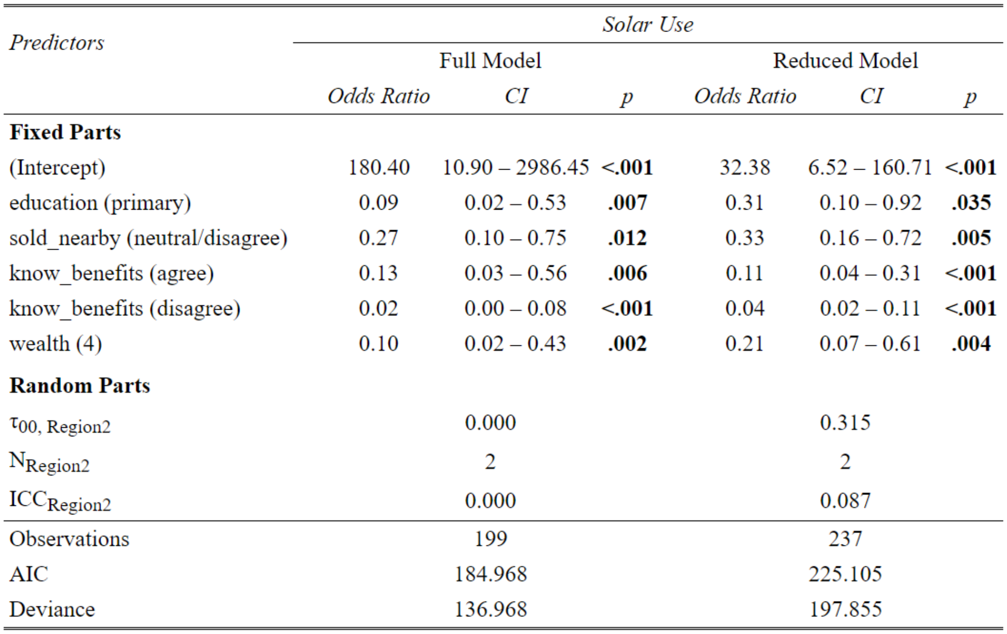
The second “other” variable included in the model was *education level*. Those who *completed primary school*, was found to be significantly and negatively associated with solar use in comparison to those who *did not complete primary school*. The odds of solar use among respondents who *did not complete primary school* was 11 times higher compared to those who *finished primary school*, when controlling for other predictors. This finding contradicts previous research which found a positive correlation between level of education and solar use [54,56]. Though significant in the full model, there was not a significant difference in solar use by education level in the bivariate analysis, so this could be a spurious correlation. However, we did find a significant (p = 0.002) positive relationship between education and grid use; among those who do not use solar power, grid power is used by 18% of those who did not complete primary school, 42% of those who completed primary school, and 66% of those who completed secondary or above. These educated solar non-users may have contributed to the model outcome above.

Gender was the third “other” variable included in the model and it was not significant. Since we surveyed heads of household regardless of gender, it follows that gender of the respondent would not be correlated with the overall household choice to use solar, even if one head is more influential in the decision than the other. We asked respondents about the degree to which they make household purchasing decisions, and responses to this question were not significantly correlated with gender. Household size was the fourth “other” variable included in the model and it was not significant. Although previous research has found household size to be positively associated with solar adoption [51], we did not find evidence of this in our sample.

3.5.5 Robustness Checks

There were 11 questions and 199 observations/respondents included in the full model, so 125 observations were removed due to respondents not identifying as the head of household, or blanks on one or more questions. There were 237 observations included in the reduced model which only included variables which were significant in the full model: *level of education*, *knowledge of benefits*, and *wealth quartile*. In this reduced model all of these variables were still significant, even with 9 fewer questions and 19% more observations, but there was a noticeable change in the odds ratio for most of the variables, as shown in Table 3.4.

Table 3.4: Comparison of significant results from full model to results from the reduced model.



Predictors	*Solar Use*					
	Full Model			Reduced Model		
	Odds Ratio	*CI*	*p*	*Odds Ratio*	*CI*	*p*
Fixed Parts						
(Intercept)	180.40	10.90 – 2986.45	**<.001**	32.38	6.52 – 160.71	**<.001**
education (primary)	0.09	0.02 – 0.53	**.007**	0.31	0.10 – 0.92	**.035**
sold_nearby (neutral/disagree)	0.27	0.10 – 0.75	**.012**	0.33	0.16 – 0.72	**.005**
know_benefits (agree)	0.13	0.03 – 0.56	**.006**	0.11	0.04 – 0.31	**<.001**
know_benefits (disagree)	0.02	0.00 – 0.08	**<.001**	0.04	0.02 – 0.11	**<.001**
wealth (4)	0.10	0.02 – 0.43	**.002**	0.21	0.07 – 0.61	**.004**
Random Parts						
$\tau_{00, \mathrm{Region2}}$	0.000			0.315		
$\mathrm{N}_{\mathrm{Region2}}$	2			2		
$\mathrm{ICC}_{\mathrm{Region2}}$	0.000			0.087		
Observations	199			237		
AIC	184.968			225.105		
Deviance	136.968			197.855		

The reduced model was also run with grid users removed, females only, or males only. A response of *disagree* to *I know the benefits of solar products* was relatively robust to these changes, as was the fourth wealth quartile, though men in this wealth quartile were much more negatively associated with solar use in comparison to women or the other models. Education was not a significant predictor of solar use for women, but it was for men. A *neutral/disagree* response to solar products are sold nearby was not a significant predictor of solar use for men, but it was for women. Our overall results, especially the interpretations thereof, are not particularly sensitive to gender or the responses of grid users.

Table 3.5: Reduced model compared with models with grid users removed, females only, or males only.

Predictors	*Solar Use*											
	Reduced Model			Grid Users Removed			Females Only			Males Only		
	Odds Ratio	*CI*	*p*	*Odds Ratio*	*CI*	*p*	*Odds Ratio*	*CI*	*p*	*Odds Ratio*	*CI*	*p*
Fixed Parts												
(Intercept)	32.38	6.52 – 160.71	**<.001**	119.92	20.53 – 700.44	**<.001**	10.00	1.44 – 69.31	**.020**	978.58	29.20 – 32794.21	**<.001**
education (primary)	0.31	0.10 – 0.92	**.035**	0.17	0.05 – 0.61	**.007**	0.82	0.15 – 4.33	.812	0.10	0.02 – 0.65	**.015**
education (secondary+)	0.32	0.09 – 1.14	.079	0.36	0.08 – 1.60	.178	1.19	0.18 – 7.80	.858	0.04	0.00 – 0.38	**.006**
sold_nearby (agree)	2.43	0.82 – 7.17	.108	2.80	0.63 – 12.54	.178	2.19	0.56 – 8.58	.263	3.89	0.44 – 34.75	.224
sold_nearby (neutral/disagree)	0.33	0.16 – 0.72	**.005**	0.24	0.10 – 0.61	**.003**	0.23	0.08 – 0.65	**.005**	0.54	0.11 – 2.64	.449
know_benefits (agree)	0.11	0.04 – 0.31	**<.001**	0.10	0.03 – 0.37	**<.001**	0.26	0.06 – 1.03	.055	0.02	0.00 – 0.15	**<.001**
know_benefits (disagree)	0.04	0.02 – 0.11	**<.001**	0.04	0.01 – 0.12	**<.001**	0.05	0.01 – 0.17	**<.001**	0.02	0.00 – 0.12	**<.001**
wealth (2)	0.87	0.31 – 2.42	.794	1.08	0.29 – 3.98	.910	0.95	0.28 – 3.26	.941	0.14	0.01 – 2.30	.170
wealth (3)	0.53	0.20 – 1.42	.207	0.39	0.12 – 1.27	.118	0.60	0.18 – 1.99	.401	0.10	0.01 – 1.52	.096
wealth (4)	0.21	0.07 – 0.61	**.004**	0.16	0.05 – 0.57	**.004**	0.21	0.05 – 0.88	**.032**	0.02	0.00 – 0.45	**.012**
Random Parts												
$\tau_{00, Region2}$	0.315			0.000			0.284			0.000		
$N_{Region2}$	2			2			2			2		
$ICC_{Region2}$	0.087			0.000			0.079			0.000		
Observations	237			201			147			89		
AIC	225.105			165.311			149.345			83.495		
Deviance	197.855			143.311			123.240			61.495		

3.6 Discussion and Conclusions

To integrate and summarize our results, we return to the Four A's framework. Our results show that overall knowledge of solar was low, there was a strong desire for more information, and having knowledge of benefits was strongly associated with solar use. Although we cannot establish causality with this study design, these findings suggest that raising **awareness** of solar technology could lead to increased adoption, especially awareness of benefits. Financial benefits should be a primary focus, including kerosene savings and productive uses of energy. Additionally, potential adopters should be made aware of product cost, so they can accurately weight it against the benefits.

Our results show that overall opinions were high, desire to make a future purchase was high, peers had a positive influence (if any), and market spoiling was not an issue. Thus, we find that **attraction** was a driver of uptake in this context, but it cannot override other barriers which were present. Although product quality was not diminishing attraction to solar, we are still concerned with the availability of low-quality solar products on the market, and any future market spoiling effect they may have. This could be mitigated in part by raising awareness on how to identify high-quality products, among both consumers and retailers.

Our findings indicate that **affordability** is only a significant barrier to solar lantern adoption for the poorest households. The short payback period of solar lanterns makes them economically attractive, except for those who lack awareness of the financial benefits, and those who have small kerosene and battery expenditures (i.e. the poorest households). Thus, affordability can be a driver or a barrier, depending on a person’s perspective, level of awareness, and wealth. This runs somewhat counter to the literature, which emphasizes affordability as a significant barrier to solar uptake. Still, payment plans for lower-cost solar products might enable the poorest individuals to afford these products.

The higher price of SHSs can present a larger financial barrier to solar use relative to kerosene or solar lanterns, but our findings indicate that **affordability** was not a significant barrier to SHS uptake, except for the poorest households. The relative affordability of SHS could be attributed to payment plans offered by international solar businesses operating in the research area. Thus, we find that affordability is not a major barrier to SHS adoption when payment plans are in place, which is in line with previous literature that stresses their importance.

Our research shows that respondents’ actual distance from a major city was not associated with solar use, and very few non-users cited availability as a barrier. However, respondents’ perceived distance to solar products was negatively associated with solar use. **Availability** does not appear to be a major barrier in the study area, except for those who may lack awareness of their nearest solar retailer. We perceived solar products to be widely available in this area. There may have been less product variety in distant locations, but the demand for solar products was still present in the most remote villages, since the need may be even greater in rural areas that have limited prospects for grid access. Availability may even be considered a driver of solar adoption, due to the efforts of solar businesses operating in the area.

It is likely that the range of our study was not far enough to see availability drop off with distance from supply hubs in the cities. Future research should address this by including study areas that are further from supply hubs. Additionally, international solar enterprises have likely had a significant impact on availability and other A's in the study area, which should be taken into consideration when interpreting these results. Our household selection process generated a sample that is not representative of the overall population in these villages. It is unclear what bias this might have introduced in terms of awareness, attraction, affordability and availability for our sample compared to the population of Arusha and Kilimanjaro regions. Though our results are not generalizable to these regions, or Tanzania as a whole, they still demonstrate the utility of the Four A's framework, and provide valuable insight into an interesting subset of Tanzanians.

The Four A's framework has proven useful for identifying the drivers and barriers of off-grid solar adoption in emerging economies. Using the Four A's as a lens to focus and interpret our results, we were able to make more concise, meaningful, and actionable conclusions. Future research should rigorously evaluate these conclusions in order to validate the utility of the Four A's framework as a tool for guiding technology adoption studies in emerging economies.

4 Impact Evaluation Proposal for an Intervention Devised to Increase Market Penetration of Off-Grid Solar Products

4.1 Introduction

After applying the Four A's to our Tanzania survey data, we found that awareness and affordability among the poorest individuals were the adoption conditions most likely to impede solar adoption in the research area. If we apply the off-grid solar theory of change (e.g. Figure 2.1) to this finding, we see that all three aspects of the overall solar enabling environment can contribute to improved awareness and affordability: information diffusion, market infrastructure, and appropriate technology.

To increase **awareness** among potential solar adopters, we need to improve information diffusion, by providing the required information we identified through our research. Economic advantage over alternatives is a key piece of information – a notable point in the ToC, which was reinforced by our research in Tanzania. Potential customers must also be aware of the actual cost of such products; this is a fundamental piece of information needed to evaluate economic advantages (i.e. cost-benefit), yet more than two-thirds of non-users in our sample lacked awareness of the cost of a solar lantern. While knowledge of financial benefits is a key adoption condition, other required information can be easily disseminated if we establish a viable and efficient means of information diffusion.

Effective means of information diffusion in emerging economies are not well established or researched. Since traditional marketing campaigns are costly and relatively unproven in these contexts, I propose novel alternatives in this chapter. The rest of this chapter takes the form of a hypothetical program evaluation funding proposal which focuses on my suggested means of information diffusion.

The proposal also calls for evaluating the impact of payment mechanisms, a key piece of market infrastructure which contributes to **affordability**. However, the need for payment mechanisms is well established (see Chapter 2), so the affordability component is not a primary focus in the hypothetical program evaluation proposal to follow. The proposal is based on an International Initiative for Impact Evaluation (3ie) proposal outline, and 3ie text appears in purple.

3ie is an NGO that “promotes evidence-informed equitable, inclusive and sustainable development. [They] support the generation and effective use of high-quality evidence to inform decision-making and improve the lives of people living in poverty in low- and middle-income countries. [They] provide guidance and support to produce, synthesize and quality assure evidence of what works, for whom, how, why and at what cost.”

4.2 Organizational Information

Name of agency that is implementing the programme or policy that will be evaluated (hereunder called the implementing agency)

Lighting Africa, a subset of the World Bank Group

Organisation type (of the implementing agency)

International Development Organization

Name of programme or policy that will be evaluated

Free Trial and Text Campaign on Increasing Market Penetration of Off-Grid Solar Products

Please list names of other implementing agencies that may be involved in implementing the programme or policy and/or in delivering the programme to beneficiaries, if applicable.

d.Light (solar product developer and wholesaler)

Tigo (mobile telecommunications company)

4.3 Summary

4.3.1 Context and relevance

a. Describe the programme or policy and the key intervention(s) that the study will evaluate.

b. Describe the importance and relevance of the research topic (please provide the most relevant and important contextual justification, which may include, but not be limited to details about the climatic, cultural, economic, ethnic, geographic, infrastructural, institutional, political and/or social factors).

c. Explain the expected policy relevance of the research questions for policymakers and implementing agencies; Potential implications of the evaluation for policy, programming, and practice.

More than a billion people live without access to electricity, and the majority reside in Sub-Saharan Africa (SSA). In 2016, members states of the United Nations adopted the 17 Sustainable Development Goals (SDGs) with the aim to eradicate poverty, protect the environment, and bring prosperity to all. One of the goals is to provide sustainable energy access to all by 2030 (SE4ALL), and this goal in turn enables many other SDGs that will be more readily achieved with widespread access to clean energy. Unfortunately, we are not on a trajectory to achieve this goal in 12 years, given the slow rate of grid expansion and restricted growth of the off-grid energy market.

Off-grid sources of energy, especially solar PV technology, are critical to achieving this goal, especially in Sub-Saharan Africa, where increases in grid access are outpaced by population growth. Off-grid solar products fall into two categories: solar home systems (SHS) that provide 10 to more than 1000 Watts of power, which can be used for lighting, cell phone charging, radios, fans, televisions, among other things; pico-solar products that provide less than 10 Watts of power for lighting and cell phone charging (sometimes).

Unfortunately, sales of pico-solar products have slowed in SSA in recent years, even though these products are the most affordable and well suited as near-term replacements for dirty dangerous kerosene lamps – which are the predominant source of light among the off-grid population in SSA. In order to reverse this trend we are developing and evaluating innovative and cost-effective market-based approaches to accelerate solar adoption in SSA.

Our proposed pilot program aims to increase uptake of pico-scale solar devices, which will displace kerosene, disposable batteries and other inferior light sources, and contribute to achieving the goal of SE4ALL. The program will employ a three-pronged approach to increase awareness and attraction of solar products:

1. We will provide a two-week free trial, wherein potential customers can gain firsthand experience of the benefits of solar products with no cost or risk.
2. We will use an automated SMS platform to send text messages to participants, which provide information on the benefits of solar, especially with regard to how much money they are saving on kerosene – both during the free trial and regularly thereafter for those who purchase a lantern.
3. We will use incentives (e.g. mobile phone airtime credit) to encourage customers to share this information with their family, friends, and neighbors (peers), who will be provided with an incentive (discount on solar product) to enroll in the free trial.

We will refer to interventions 2 and 3 as a “text campaign” going forward, and the following is an example text message: “You have saved about $1.25 on lighting and phone charging in 1 month of using your solar product. Tell your family and friends how much you have saved, then ask them to text this special code: ZADVBHHG to 123-456-7890. They will get a 5% discount on a solar product, and you will receive $1 in airtime credit for each person that purchases a solar product after texting this special code." This will incentivize the diffusion of information on financial benefits among peers, while also promoting additional enrollments in the free trial. In the future, our program will increase affordability, especially for the poorest individuals, by providing them with the option to pay for a lantern in four weekly installments (payment plan).

Though they provide relatively little energy, pico-solar products will provide a better quality of light/life until people can afford larger solar products or are connected to the grid. These products will deliver meaningful savings on kerosene and battery expenditures, with payback periods as short as 3 months [108]. The short payback period of solar lanterns and other pico-solar products will enable these technologies to completely displace kerosene lighting without relying on subsidies. This will have a meaningful impact on climate change in the short-term because kerosene lanterns produce a significant amount of black carbon, a short-lived pollutant that is 700 times more potent than carbon dioxide.

4.3.2 Evaluation questions of interest

a. List the main research questions, associated outcomes and impacts of interest.
b. Identify the relevant subpopulations that will be examined in this evaluation.

The main evaluation questions of interest are:

1. Can solar retailers significantly increase pico-solar sales by providing a free-trial period and employing a text campaign?
2. How does pico-solar use affect kerosene and other lighting expenditures?

The primary outcome of interest is uptake of solar products as a result of our program. The primary impact of interest is reduced expenditures on kerosene, batteries, and other lighting related expenses.

The subpopulation of interest in this evaluation is the off-grid population of northern Tanzania, so we will exclude urban areas from the study. The effectiveness of the text campaign aspect of our program relies on mobile phone ownership and the ability to receive and read texts, so this subpopulation is our primary focus. As of 2017, 88% of adults in Tanzania had mobile phone access [118]. Those who do not own mobile phones will not be excluded from participating in the free trial aspect of the program, or from being referred by peers in person. Going forward we will devise ways to better reach households who do not own mobile phones.

4.3.3 Empirical data and methods

a. What mix of methods will be used to test assumptions and make causal claims in the programme theory of change?
b. What is the identification strategy (how will the attributable change caused by the programme or policy be estimated)?
c. What are the key quantitative and qualitative sources of data for this study?
d. What is the sample size that the study will use to examine its key questions? Please indicate for which outcomes the study is powered.

We will use a randomized controlled trial (RCT) to establish causality when evaluating the impact of our program and validating our theory of change. We will also use qualitative methods to answer secondary questions, improve our understanding of the “why” behind our evaluation outcome, and gain insight into how the program can be improved going forward. Our program evaluation will be split into three phases:

In Phase I, we will randomly select 16 wards from all non-urban wards across northern Tanzania into an equal number of treatment and control groups, and randomly select 45 households from within each ward. Households in the treatment wards will receive the option to participate in the free trial and text campaign outlined above. Uptake among treatment and control households, lighting expenditures, and number of peer referrals are the primary quantitative outcomes of interest in Phase I, and the study is powered to assess the first two. Households in both groups will be surveyed and briefly interviewed in order to build our understanding of the reasoning behind their decision, and to provide insight into some of our secondary questions. If our program has a significant effect on uptake compared to the control we will proceed to the Phase II evaluation.

In Phase II, we will attempt to replicate the success of Phase I through market-based sales by recruiting local retailers to offer our program and products. We will randomize at the ward level only and will encourage all relevant retailers in a given ward to participate in our program. Participating retailers in treatment wards will offer the free trial and text campaign to customers at the point of sale. The primary outcomes of interest are the number of solar sales, and number of sales resulting from peer referrals. We will use a factorial RCT design to compare the effect of the free trial, the text campaign (i.e. texting information on benefits and incentivizing peer-to-peer information sharing), and the combination of both, and the study is powered accordingly. In this phase we will also quantify the costs associated with a free trial and text campaign, thereby allowing us to assess the cost-benefit of these interventions. In this phase, qualitative data will be collected from solar retailers regarding their opinions of our program, their desire to participate, and what they would like to change. Additional qualitative and quantitative data will be collected from customers through a brief interview at the point of sale.

In the Phase III evaluation we will test the effect of a payment plan in combination with the most effective or most cost-effective treatment identified in the Phase II evaluation. We will also explore the possibility of phasing out the free trial component to see if the text campaign can sustain adoption after a certain number or proportion of adopters has been reached in an area. In this phase we will work to expand the program to other countries in Sub-Saharan Africa. We are not yet requesting funding for this phase, as we believe the success of our Phase I and Phase II evaluations will enable us to forge partnerships that will allow us to carry out the Phase III evaluation through the support of market-based actors.

4.3.4 Evaluation Context

Briefly describe the policy or implementation topic that the proposed impact evaluation will address. In what way is the evaluation likely to inform national, regional or global policy contexts.

If relevant, please describe how the evaluation will specifically help address important policy or programmatic challenges being faced by the implementing agency.

The UN SDGs and SE4ALL represent a global call to action. Lighting Global is working to answer this call by supporting market development for solar products. These efforts include providing market intelligence that demonstrates the business opportunities in this sector, and imparting quality assurance through our quality standards and testing programs. We intend to further support business development by providing information on best practices and innovative approaches for selling solar products. Through this pilot program and evaluation, we will develop new tools for marketing and raising awareness in an effective, affordable, and scalable way. If our program proves to be effective, we will work to promote the use of free trials and the text campaign platform among local and international solar businesses through cooperation with the relevant stakeholders. In this way, we will broaden the impact of our program and accelerate action toward achieving SE4ALL.

4.4 Theory of Change

Our program was developed using the guidance of our theory of change (Figure 4.1), which elucidates the change pathways for achieving increased uptake of off-grid solar products.

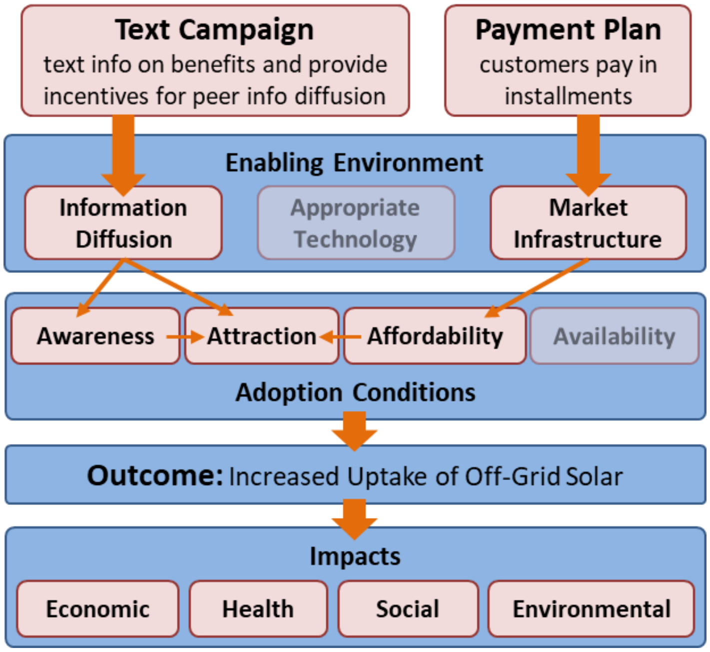


Figure 4.1: Theory of change for increased off-grid solar adoption through a text campaign and a payment plan

4.4.1 Prior Formative Work for the Evaluation

Has any prior formative or preparatory work been done to inform the questions and targeted outcomes for this evaluation? If yes, describe it in brief. You may (also) attach one document to expand on the formative work. Previous formative work may include literature review, field work, prior implementation experience, discussions with practitioners and implementers, and relevant descriptive statistics.

We developed our theory of change (ToC) based on an extensive literature review. We previously carried out survey research in Tanzania in order to identify the barriers to solar adoption in the context of this ToC. We identified awareness, especially awareness of financial benefits as a significant barrier to solar adoption. As such we have developed the proposed pilot program as a means of addressing the issue of awareness.

Another barrier we identified through this research was affordability of the poorest of the poor. At the same time, we found that wealth was not a barrier for most individuals, even among those living well below the poverty line. As such, we believe that a payment plan is not required in order to see a significant impact in Phase I and II evaluations. Since a payment plan will better allow us to reach the poorest of the poor while further enhancing the program’s impact on solar adoption, it is the subject of our Phase III evaluation.

4.4.2 Knowledge Gap

Please briefly outline the knowledge gap for the implementing agency or other key decisionmakers at the relevant levels (community, national, regional and global) that the proposed evaluation will address.

While there are many innovative business models in the solar marketplace in emerging economies, they have not yet shown a proven path to success. Additionally, many of these business models focus on technical innovations, while they may be failing to address the fundamental drivers of successful strategic innovation in emerging economies: awareness, attraction, affordability, and availability. In terms of affordability, we know that pico-solar products are cost effective relative to kerosene and disposable batteries, but the upfront cost can be an issue in the absence of a payment plan. We know that the issue of availability will be addressed as the solar market develops and becomes more financially viable. We are lacking knowledge in regard to the most effective, affordable, and scalable ways of increasing awareness and attraction – something we will change through the proposed evaluation. We will share our findings with the relevant decisionmakers.

4.5 Evaluation Design

4.5.1 Evaluation Questions

Please list the evaluation question(s) of the proposed study. Also list the primary and secondary outcomes and impact variables that the study will assess.

Note: outcome/impact variables are underlined

Phase I Primary Questions:

- Does a free trial and text campaign significantly increase solar adoption?
- How does solar use affect kerosene and battery expenditures?
- Does the text campaign lead to participation in the free trial among peers?

Phase I Secondary questions:

- What is the rate of product damage and theft?
- Does the baseline level of solar use affect the impact of this program?

- Additional secondary questions can be found in Appendix 6.2.2

Phase II Primary Questions:

- How are solar sales affected by the free trial alone, the text campaign alone, and the combination of both?
- Which of these interventions are most cost-effective?
- Does the text campaign lead to increased participation in the free trial among peers?

Phase II Secondary Questions:

- Does our program lead to increased use of mobile phones in treatment wards, including mobile money transfers, not including texts and money sent as a direct result of the program?
- How does solar use effect kerosene and battery expenditures?
- Additional secondary questions can be found in Appendix 6.2.2

Phase III Primary Questions:

- Do payment plans significantly increase solar sales?
- Additional Phase III questions can be found in Appendix 6.2.2

4.5.2 Mixed Methods

For 3ie, it is important that researchers employ a mix of methodological approaches and data sources to assess the factual and counterfactual and the intended and unintended consequences to help answer questions relevant to implementing agencies and decisionmakers: Describe the range of quantitative and qualitative methods, data collection tools and techniques that will be used in the impact evaluation. If relevant, please describe any secondary data that may also be used. Elucidate how various data types and sources will be integrated to generate, analyse and, interpret results.

We will use mixed methods in our evaluation. We will use a randomized controlled trial to answer most of our primary questions, by measuring the effects of our program relative to the counterfactual represented by the control group. We will use additional quantitative methods, such as regression modeling to answer some of our secondary questions. We will use qualitative methods, such as interviews with household members, in order to answer other secondary questions and gain additional insight into the success or failure of our program. We will also use qualitative methods to validate and enhance our understanding of the quantitative results, and improve our program going forward. We will employ participatory research methods to include the perspectives of local solar retailers.

Phase I will require an initial census of households within each of these wards, in order to locate the pool of households from which we will draw our random sample. We will take this opportunity to quantify the lighting sources in use across the ward at baseline, and briefly collect basic demographic data. We can use this information to compare the characteristics of the treatment group to those of the control group, and compare the characteristics of households randomly selected within a ward to those of the entire ward.

We will make an initial visit to each of the randomly selected households in order to carry out a brief survey to gather relevant demographic, socioeconomic, knowledge, and opinion data. We will ask the households to track lighting expenditures over the next two weeks and compensate them appropriately for their time and effort in doing so. Where possible, we will attempt to collect this information via text message on a regular basis, but physical log sheets will also be made available.

After two weeks we will then return to each of the selected households and deliver a brief scripted sales pitch. At this point treatment households will be offered a no-obligation free trial with their choice of one of three d.Light products - see Appendix 6.2.1 for more details. We will inform them that we will return in two weeks, at which time they can either pay for the product or return it. Control households will be offered the product for immediate purchase, but we will also inform them that we will return in two weeks, at which time they will have another opportunity to make the purchase. This gives both groups the same amount of time to save money.

After our sales pitch and offer, we will carry out a brief interview to get a better understanding why they accepted or declined our offer. We will ask all households to continue tracking their lighting expenditures over the next two weeks. In two weeks we will return to see which treatment and control households have decided to accept the offer. At this point we will conduct another brief interview and collect any lighting expenditure data that was physically logged.

Immediately after the free-trial period we will calculate/estimate the amount of money that free-trial participants saved over the course of two weeks. We will text this information to those who chose to adopt, along with a message encouraging them to share this information and a special ID code with their peers. If peers text us the unique ID code and decide to purchase a product they receive a discount and their referrer will receive an appropriately sized airtime voucher as an incentive. We will track the number of peers who text us, and the ID codes.

We will begin Phase II with a participatory approach that includes local stakeholders, especially existing solar retailers. We will work with retailers in a subset of control and treatment wards, before beginning the Phase II treatment in any wards. Through this collaboration, we will better understand if there are more pressing issues that local retailers are facing which need to be addressed in advance of our program. Local collaborators will also help shape the customer survey/interview, such that it is a length that they are comfortable with and provides information that they are interested in. Engaging local retailers is an important aspect of scaling up the impact of our program in the future, so it is critical that we include their perspectives in the evaluation and adjust the program based on their insights.

Local solar retailers who choose to participate in the program in the treatment wards will offer free trials and enroll customers in the text campaign. Participating retailers in treatment and control wards will carry the same d.Light products[10], keep records of their solar product sales, and briefly survey solar adopters. We will appropriately compensate retailers for their time and effort, beyond the profit they stand to make selling our products.

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[10] Possibly different from the three products used in Phase I, based on feedback from retailers and customers. Retailers can continue to carry their other products, but only ours will be eligible for the free trial.

We will assess costs incurred due to the free trial, including losses due to damage, theft, non-payment, and delayed payment during the free trial[11]. We will also assess costs associated with accepting payments via mobile money, and sending text messages and offering incentives for the text campaign. Additionally, we will survey and interview participating retailers to assess the extra time and effort required to administer our program, not including the effort in executing customer surveys. This will allow us to assess the cost-benefit ratio for each of the treatments from the perspective of solar retailers. We will also account the benefits that mobile telecoms may realize, and leverage these benefits to gain financial and logistical assistance from telecoms when going to scale

The variety of data sources and collection methods will add confidence to experimental findings, assuming they align, thereby strengthening internal validity. Integrating the different sources and methods will also provide a richer understanding of the change process, and give insight into potential improvements that could be made going forward. Additionally, our qualitative methods will allow us to capture unintended consequences that might not be captured by our quantitative impact metrics.

4.5.3 Identification Method and Internal Validity

Please describe the identification strategy that will be used to measure the causal change in outputs, outcomes and/or impacts that this evaluation aims to quantiatatively estimate. Please discuss how key sources of bias (placement bias, selection bias, attrition bias) and other sources of bias, including externalities, spill overs, contamination issues, including Hawthorne effect and John Henry effects will be controlled, mitigated or eliminated.

We will employ a randomized controlled trial in all three phases of our proposed evaluation. This will allow us to establish causality when evaluating the outcome and impacts of our program. Randomization will minimize selection bias, and through the course of our research we will work to minimize issues that could contribute to selection and withdrawal bias. For

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[11] These losses were minimal in a study of free trials on cookstove adoption in Uganda, with buyers paying 90% of what was owed overall for the free trial offer, and 97% of what was owed for the free trial + payment plan offer.

example, we will make a concerted effort to follow up with households who are not home when we visit, rather than excluding or replacing them.

Ascertainment bias has the potential to influence our Phase I results, since enumerators will know which group a household is assigned to in order to provide the correct sales offer. We will train enumerators to be aware of potential biases they may introduce consciously or unconsciously during the sales pitch or data collection, so they can work to minimize this bias. Fortunately, our primary outcome measures are objective and should not be subject to observer bias. Ascertainment bias will be less of an issue in the Phase II market-based approach, as retailers will be unaware of the offers that are being made by retailers in other wards. We will minimize ascertainment bias that may be introduced by researchers after data collection by filing a research plan before collecting data, abiding by the planned analyses, and keeping researchers blind to the group identities until the analyses are complete.

We will minimize spillover effects by randomizing at the ward level, and we will account for possible spillover effects at this level by testing if outcomes in control wards are a function of distance to treatment wards. By minimizing spillover effects and blinding households to their treatment assignment, we will minimize the John Henry effect. The Hawthorne effect could introduce bias in the door-to-door approach of Phase I, but it should not be a significant source of bias in Phase II because of the market-based approach and its less overt observations.

4.5.4 Sampling Strategy

Please describe the sampling strategy that will be used for this impact evaluation.

For the first phase of our evaluation, we will employ a cluster sampling method where the primary sampling units are randomly selected wards, which are composed of two to five villages in most cases. Wards in urban areas will be excluded from the sampling pool. Wards will be randomly selected into treatment and control groups. We will not randomize treatment at the household level because we do not want spillover effects to impact the purchasing decisions of households who know that their neighbor received a different offer. Additionally, ward-wide treatment is more realistic since our program will be available to whole villages and wards when implemented at scale.

Though the program will be implemented at the ward level, measurements will be made at the household level for the Phase I evaluation. We will obtain a complete list of households within each selected ward with a door-to-door census at the beginning of the evaluation. We will then randomly select households within the primary sampling units, so that we obtain a representative sample. In Phase II we will randomly select a new set of wards and randomly assign them to one of three treatment groups or the control group.

4.5.5 Sample Size Calculations

Please present the sample sizes that you will use to estimate your main outcomes. To discuss these sample sizes, provide parameter values for the following variables that will be used to inform your calculations. Also provide justifications for using these parameter values.

a. Expected baseline values (mean and variance) for main variables (output(s),outcome(s)and/or impact(s)) being assessed by this impact evaluation;
b. Expected effect size or minimum detectable effect;
c. Levels of alpha and beta (significance and power) assumed;
d. If relevant, number of clusters and intracluster correlation coefficient and justification;
e. If relevant, expected takeup rates; and
f. Expected treatment and study sample attrition.
g. If relevant, subpopulations that will be examined. Please indicate if the evaluation is powered to examine consequences for these subgroups.

Our Phase I trial will have 8 treatment wards and 8 control wards, and each will contain 45 households, for a total sample size of 720 households. This sample size was based on power calculations for key outcome variables: proportion of households accepting our offer and savings on lighting expenditures.

We estimate offer uptake in the control group to be 10% based on average uptake for a the GiveWatts program, which offers solar lamps through schools in Tanzania and Kenya [119]. We set the minimum detectable effect to 10%, as a smaller effect might not be worth the effort and expense involved in implementing this program at scale. We believe that our program will have impact in excess of this because cookstove uptake was 7 times higher among those offered a free trial as part of an RCT in Uganda (cookstove uptake was 11 times higher among the those offered a free trial and payment plan) [49]. Solar products have fewer barriers to adoption compared to cookstoves [22], thus it is reasonable to assume that our intervention will at least double the uptake of our solar offer. Assuming a conservative value of 0.25 for the coefficient of variation, and setting the number of households within each cluster at 40, we calculate that 7.35 clusters (wards) are needed in each group in order to achieve a two-tailed significance level of 0.05 and power of 0.80.

Using values of 8 clusters per group, 40 households per cluster, 0.25 for the intra-cluster correlation coefficient, 0.05 for the significance level, and 0.8 for power, we find that we will be able to detect an effect in lighting expenditure as long as the standard deviation of the effect is at least 3% smaller than the magnitude of the effect. For example, if the effect on lighting expenditures is a $1 reduction, the standard deviation of this effect would need to be $0.97 or less in order for our study design to have 80% or greater power to detect this effect. A recent RCT in Tanzania showed that solar lanterns saved 486 TSh ($0.22) on lighting expenditures in a typical week, with a standard deviation of 187 TSh ($0.09) [119], thus our study design would have a high likelihood of being able to detect this effect. Further details on our sample size calculations are shown in Appendix 6.2.3.

We expect to have no attrition at the ward level, and we have increased the household sample size to 45 per ward in order to account for possible household attrition. We will calculate the sample size required for the Phase II evaluation based on the results of Phase I.

4.5.6 Impact Heterogeneity

List specific subpopulations for whom you hypothesise there may be diverse effects of the programme or policy. Among these, also mention those that will be measured by this evaluation. Of particular interest to the evaluation are socially and structurally marginalised and vulnerable subpopulations as well as other priority subgroups affected by the programme or policy. These may include (but are not restricted to) differentiated data and analysis for gender and age subgroups.

We hypothesize there may be different effects for subpopulations based on their current source of light. Our program might be more effective for kerosene users compared to battery users, because the financial, health, and well-being benefits of going from kerosene to solar are larger than the benefits of going from battery power to solar. In this way, our program will positively affect those who are the most marginalized in terms of their lighting source and level of energy access.

We also hypothesize there may be different effects for subpopulations with different levels of wealth. Solar uptake among the poorest quarter of the population may be lower relative to wealthier individuals in the Phase I and Phase II trials, but this marginalized population will be targeted in the Phase III payment plan evaluation and when scaling-up the program. We will collect information on sources of light and assess wealth during our baseline and follow-up surveys, and account for these sources of heterogeneity in our regression analysis.

4.5.7 External Validity

In order to clarify the potential transferability impact findings, please describe the extent to which the chosen study sample represents the broader context and subnational, national and/or international populations.
To what extent will it be possible to use the results of the evaluation to inform this broader (outofsample) context? Please briefly present reasons that this may be valid or reasons for being circumspect in transferring impact findings.

The theory of change underlying our program is generalizable to other countries in SSA. Furthermore, our program addresses fundamental preconditions to adoption which need to be addressed across SSA, namely awareness and affordability. Thus, if our program proves successful in Tanzania, we believe it will prove successful in other countries where there is a significant off-grid population who has limited awareness of the benefits of solar and limited access to payment plans. The degree to which it is successful in other locales is likely to vary depending on factors such as the current level of market development and penetration for solar products, levels of grid access, governmental policies, political and economic stability, etc. The prevalence and use of mobile phones across different countries is another factor that would affect the impact of the text campaign, and thus the external validity. Additionally, our evaluation is not generalizable to urban areas since we excluded urban wards, but these populations may be less in need of off-grid energy solutions.

4.6 Policy Relevance

Please describe the process employed by the team while preparing this proposal that ensured the involvement of and engagement with the agency implementing the programme or policy. Also mention other key actors that are expected to use the findings of this study. Please list these actors and indicate how they contributed to the development of the proposal if at all. How is this engagement reflected in the evaluation questions you have proposed above?

We developed a stakeholder map (Figure 4.2) in order to identify the key actors who would be interested in the findings of this evaluation. We reached out to these actors, some of whom became involved in this pilot project: Tigo and d.Light.

		Interest	
		Low	High
Power	High	National Government	Mobile telecoms International solar retailers Large solar manufacturers and distributors Bilateral/multilateral aid orgs.
	Low		Local solar retailers

Figure 4.2: Stakeholder map identifying important actors.

Tigo is a mobile telecommunications provider, who will facilitate in developing the automated text messaging platform that will be the basis of our text campaign. They also have a mobile money tool, Tigo Pesa, which will allow customers to pay for solar products via text message – an enabling technology for collecting payments after the free-trial period in Phase II. Our question about the possibility of increased use of mobile phones and mobile money transfers in treatment wards is of interest to this stakeholder, and will be important for engaging other mobile telecoms when going to scale.

d.Light develops, manufacturers, and wholesales a variety of pico-solar products and SHS. They will supply the range of products we will offer in the course of our program evaluation. They are interested in enhancing the effectiveness of retailers, which will have positive impacts on other businesses in the solar supply chain, including themselves. d.Light has contact with a number of retailers, large and small, and they will promote the use of our program among these retailers, pending the outcomes of this evaluation. If our program has positive impacts, we will be able to engage other solar businesses who will contribute to scaling up the program, and allow us to evaluate it in different countries and contexts.

4.6.1 Influence on policy, programming and practice

One demonstration of how the study may potentially influence change is that key decisionmakers, including the implementing agency, programme managers and beneficiaries are aware of, understand and can make use of the evaluation findings. Please briefly indicate what attributes

of the implementing agency, context and timing of the evaluation make it likely that the study and its findings will inform programme or policy decisionmaking?
Please also highlight the planned role of the evaluation team in ensuring timely engagement with stakeholders during the study period that is likely to ensure ownership and understanding of the study and promote the uptake of its findings among key decisionmakers and beneficiaries.

It is critical that we alter the trajectory of solar uptake in order to reach the goal of SE4ALL. Our program could prove to be a viable strategy for increasing uptake of pico-solar and other off-grid solar products. Thus, the outcome of this evaluation will influence policy, programming, and practice for a range of stakeholders who would benefit from such a strategy, including those who are involved in the solar market and those who promote clean energy access and human development in general. In order to appeal to these stakeholders, we have developed a program that is easily scalable. A key part of the program operates via mobile phones which already reach 88% of adults in Tanzania [118]. The automated nature of the text campaign requires minimal input from retailers, making it appropriate for small local retailers and large multi-national retailers alike.

The program will benefit a number of stakeholders, who will be capable of promoting and spreading the use of the program. For example, mobile telecoms will benefit from increased revenue generated through the text messages and mobile money payments made directly as part of the text campaign and payment plan. It is also likely that mobile telecoms will see indirect benefits, such as increased phone use among customers who can maintain their phone charge with a solar product, and increased use of mobile money as people become more familiar with it through making payments for solar products. Mobile telecoms will be key allies in scaling up the program, since they already well established in terms of influence, brand recognition, and distribution networks.

Additionally, we believe that the core aspects of this program (free trial, text campaign, and payment plan) could be easily adapted to larger solar products and other products that contribute to improved lives and livelihoods. That is because the program addresses the fundamental drivers and barriers of product adoption in emerging economies in a potentially generalizable way. As such, this program evaluation may influence the policy, programming, and practice of a wide range of stakeholders. Additionally, we will inform and assist regulators who can develop policies and regulations to enable greater programmatic impact.

4.7 Projected Impacts

The economic, health, social, and environmental impacts of solar lighting and phone charging products are outlined in the table below. Many of these values come from a RCT with 2067 households in the Magu district of Tanzania (each district is made up of several wards). Appendix 6.2.4 contains a table with additional evidence of impacts, including evidence from other countries and evidence from less rigorous studies. It is worth noting that our lighting expenditure savings estimate is much more conservative compared to industry estimates, which are shown in the table in the appendix.

Table 4.1: Impact of pico-solar products

ECONOMIC		
Financial savings		
Lighting and phone charging per product	$19.92/year	[119]
Additional Income or Productivity		
Increase in household income	25% ($95/hh-year)	[119]
Job creation per million lanterns	17,800	[120]
HEALTH		
Indoor Air Quality - indoor concentration of $PM_{2.5}$ relative to wick lamps		
With improved cookstoves or outdoor kitchens	39% to 79% lower	[121,122]
With traditional cooking methods	7.5% lower	[119]
SOCIAL		
Women's Empowerment		
Women working outside the household	26% higher	[119]
Women earning income outside the household	16% higher	
ENVIRONMENTAL		
CO_2 equivalent emissions avoided (including black carbon and CO_2)		
Kerosene wick lantern	941 kg CO_2e/year	[6,44,123,124]
Kerosene hurricane lantern	124 kg CO_2e/year	

If our program evaluation proves successful we will work to promote its use in Tanzania. We estimate an increase in annual sales of 100,000 products in the first year of the program, which would increase to 1,000,000 additional products in the fifth year relative to sales in the counterfactual scenario. For reference, an estimated 1.2 million pico-solar products were sold in Tanzania in 2016. The projected annual and cumulative impacts are shown in Table 4.2.

Table 4.2: Projected impacts as the program is rolled-out in Tanzania over five years. Impacts do not include baseline sales in these years, just the increased number of sales that result from the program.

	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Cumulative**[12]
Increased Annual Sales	100,000	250,000	500,000	750,000	1,000,000	2,600,000
Saved Lighting Expenditures ($ million/year)	1.99	4.98	9.96	14.94	19.92	101
Increased Income ($ million/year)	9.50	23.75	47.50	71.25	95.00	480
Additional women earning income (#/year)	8,550	21,375	42,750	64,125	85,500	222,300
CO_2 equivalent emissions avoided[13] (metric tons CO_2e/year)	33,847	84,617	169,233	253,850	338,467	1,709,257

We estimate that we could increase sales by a total of 2.6 million products over the course of the first five years of the program in Tanzania alone. As a result, rural households would experience over one-half billion in cumulative financial benefits, with almost one-quarter million additional women earning an income that contributes to their financial independence and empowerment. In order to have a meaningful impact on indoor air quality, this program would need to be implemented in conjunction with a clean cooking intervention. Still, 1.7 million metric tons of CO_2 emissions would be avoided, which is the equivalent of 364,000 passenger vehicles driven in the US over the course of a year. Since we intend to promote the program in other countries, the total benefit will be much greater, and it will help put us on track to achieve SE4ALL by 2030.

4.8 Timeline

The general timeline for Phase I & II is shown in Figure 4.3, and the detailed timeline for Phase I is shown in Figure 4.4.

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[12] Assumes a three-year product lifespan, which is 1.5 times the length of typical warranty periods on pico-solar products

[13] Assumes one-third of sales displace a kerosene wick lantern and one-fifth displace a kerosene hurricane lamp, with the rest replacing disposable batteries and supplementing, rather than replacing, kerosene.

Figure 4.3: General timeline for Phase I & II

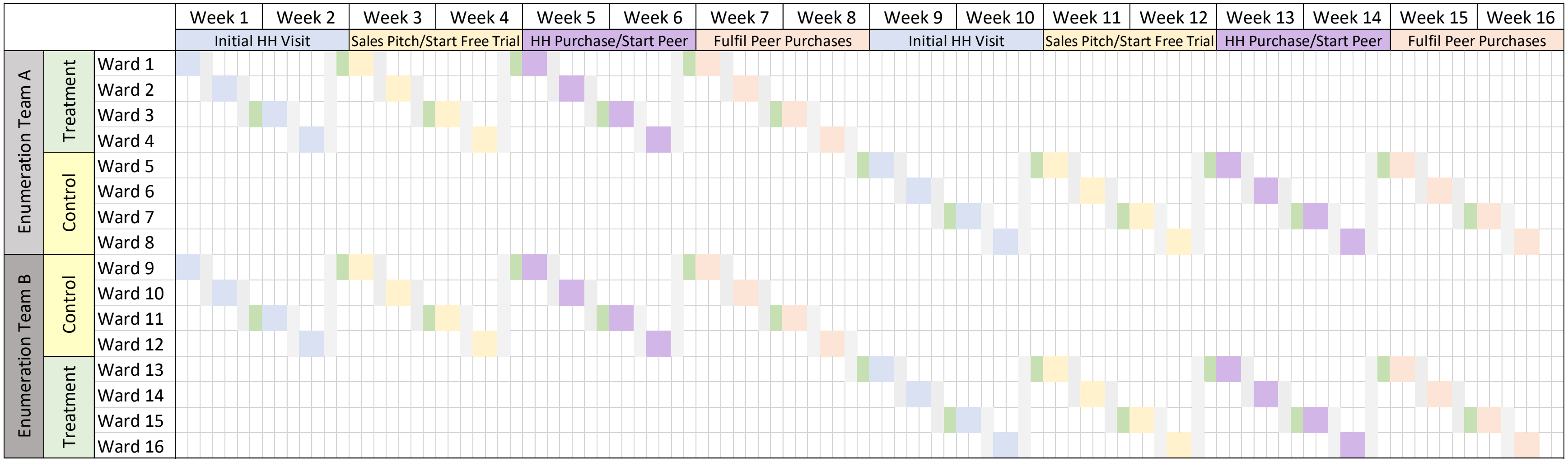

Figure 4.4: Detailed timeline for Phase I, where light grey represents travel, green represents time off, and other colors are indicated in the figure.

Phase I runs from July through October of 2019, with preparations for Phase I occurring in the preceding months, and data analysis occurring in the following months. We chose this time period because harvest season is from July to September (see Figure 6.4) [125]; since agriculture is the primary source of income for many Tanzanians, it is likely that they will have more available income during these and the ensuing months, and may be more likely to make a purchase at that time. We will also carry out Phase II during the same time period in 2020. Our research results will not be generalizable to the whole year, but they will be relevant to the period of time when people might be more likely to purchase a solar product, even in the absence of our intervention. Treatment and control wards will be visited simultaneously so that seasonality will not affect internal validity.

In order to meet this timeline, we will need two teams of enumerators with four enumerators on each team. Each enumerator will have to visit 5 to 6 households each day, which is within reason. Enumeration in Phase I will require approximately 3,000 to 4,000 person-hours, not including travel time.

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6 Appendix

6.1 Chapter 3 Appendix

6.1.1 Tanzania Background

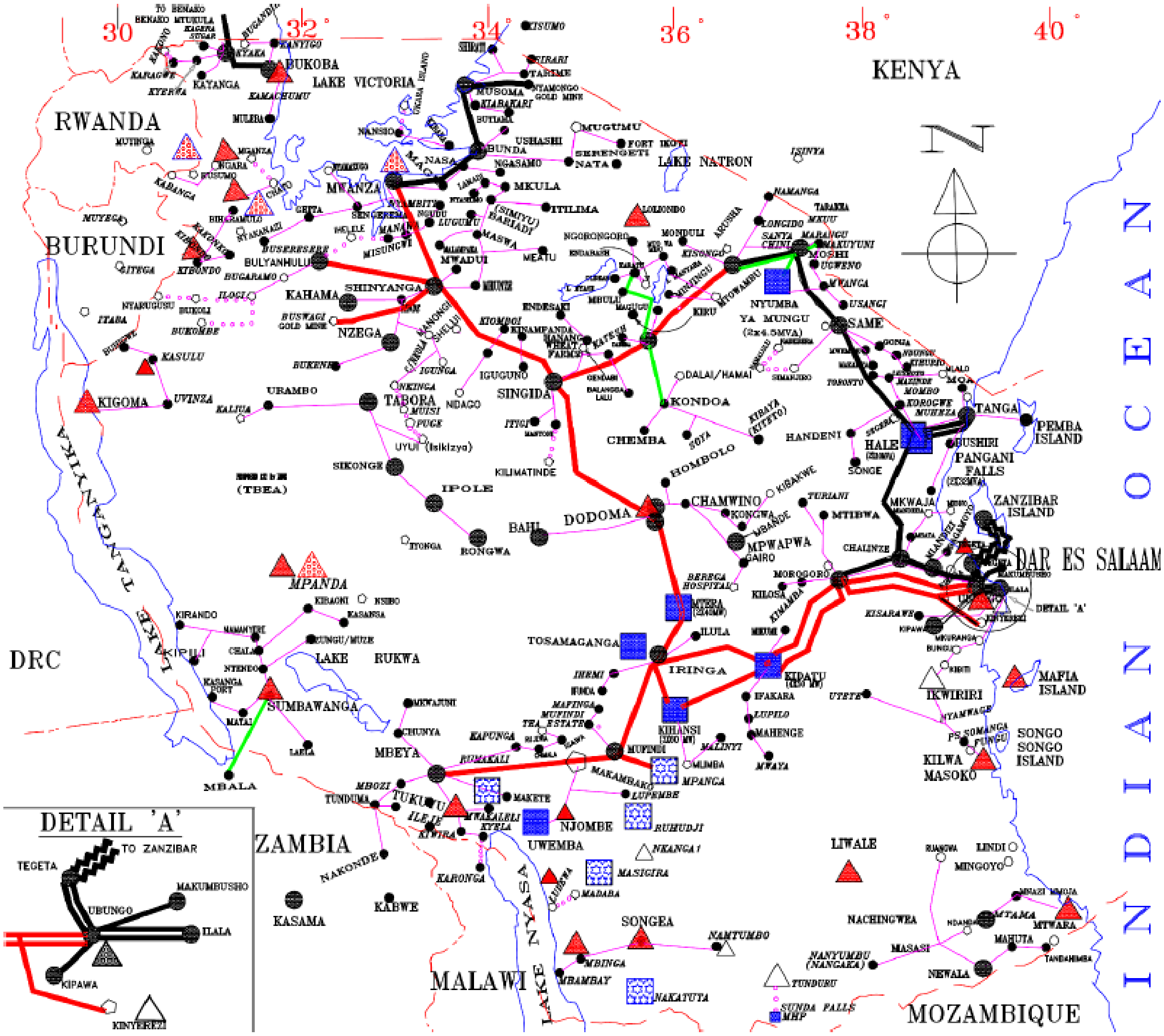

Figure 6.1: Current (2016) map of the Tanzania national grid. Note: there was no legend associated with this map [126].

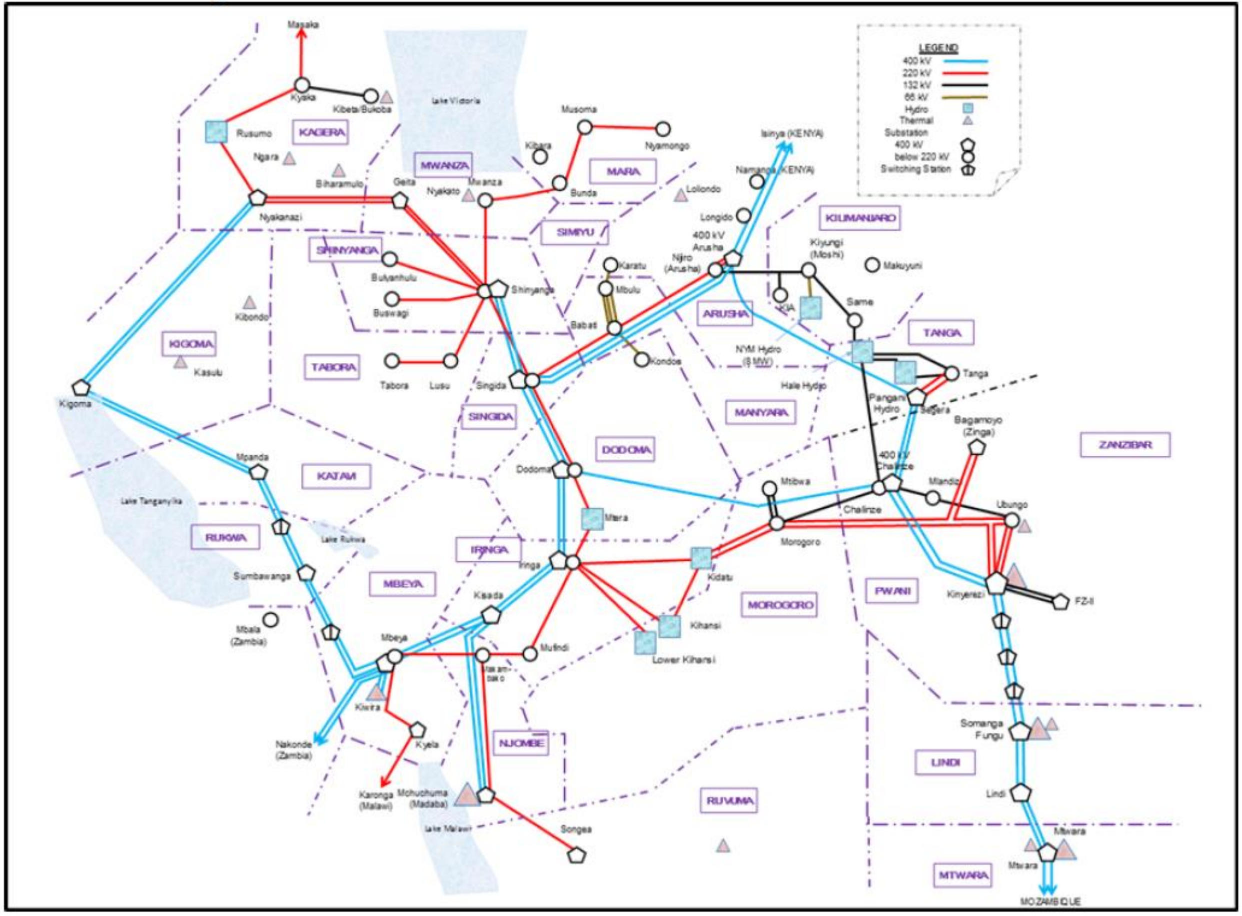

Figure 6.2: Projected 2020 map of the Tanzania national grid [126].

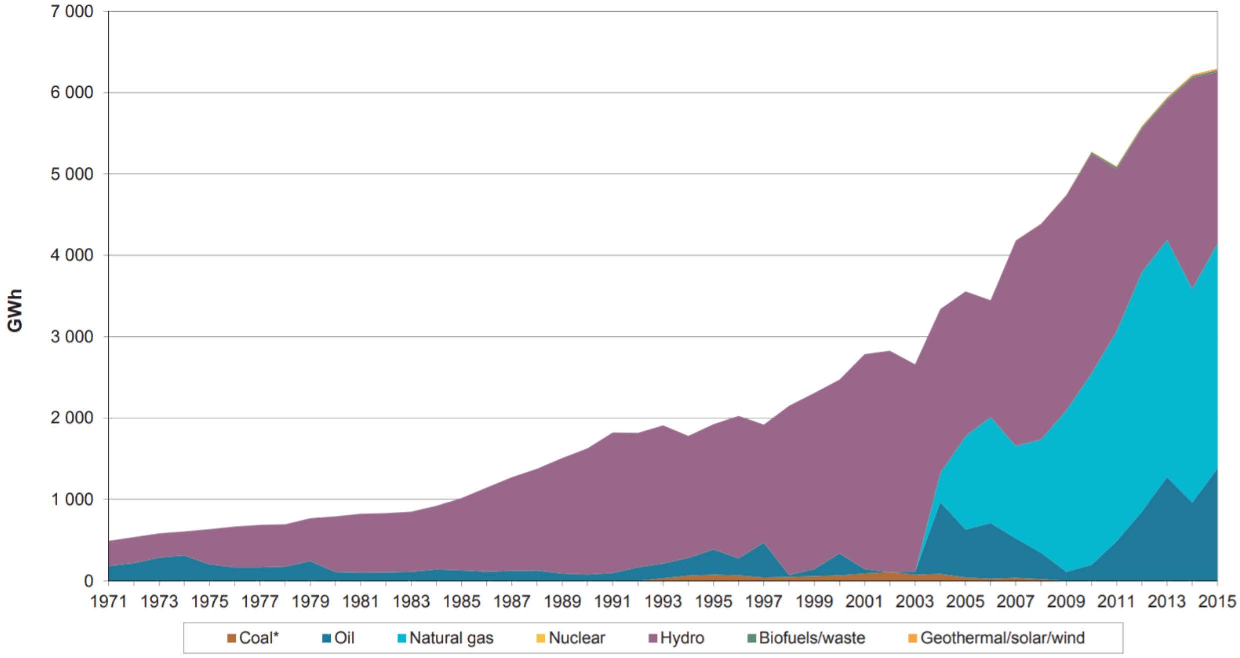

Figure 6.3: Tanzania electricity generation by fuel [127].

6.1.2 Model Results

Table 6.1: Full model results

Predictors	*Solar Use*		
	Household Heads Only		
	Odds Ratio	*CI*	*p*
Fixed Parts			
(Intercept)	180.40	10.90 – 2986.45	<**.001**
household	1.03	0.83 – 1.27	.779
education (primary)	0.09	0.02 – 0.53	**.007**
education (secondary+)	0.16	0.03 – 1.03	.054
sold_nearby (agree)	1.78	0.38 – 8.39	.469
sold_nearby (neutral/disagree)	0.27	0.10 – 0.75	**.012**
will_purchase (agree)	1.97	0.21 – 18.70	.556
will_purchase (neutral/disagree)	1.06	0.34 – 3.31	.919
know_benefits (agree)	0.13	0.03 – 0.56	**.006**
know_benefits (disagree)	0.02	0.00 – 0.08	<**.001**
quality_available (neutral)	0.73	0.21 – 2.48	.611
quality_available (disagree)	1.96	0.44 – 8.76	.379
identify_quality (neutral)	0.61	0.12 – 3.10	.555
identify_quality (disagree)	1.12	0.26 – 4.75	.883
identify_quality (strongly disagree)	0.68	0.16 – 2.83	.595
family_using (10-19)	0.60	0.15 – 2.37	.467
family_using (0-9)	0.44	0.13 – 1.55	.203
family_broken (none)	0.66	0.24 – 1.85	.428
wealth (2)	0.60	0.16 – 2.32	.460
wealth (3)	0.59	0.15 – 2.33	.452
wealth (4)	0.10	0.02 – 0.43	**.002**
gender (female)	1.25	0.44 – 3.56	.680
distance	1.03	1.00 – 1.07	.069
Random Parts			
$\tau_{00, \text{Region2}}$	0.000		
N_{Region2}	2		
ICC_{Region2}	0.000		
Observations	199		
AIC	184.968		
Deviance	136.968		

6.2 Chapter 4 Appendix

6.2.1 d.Light Products Offered

(information and pictures from http://www.dlight.com/solar-lighting-products/)

“**S3**” – Approx. $8 retail

4-12 hrs of light per charge, 4x brighter than kerosene, integrated solar panel, effective work or spotlight – for children’s studies, for example.

“**S30**” – Approx. $8 retail

3-12 hrs of light per charge, 6x brighter than kerosene, integrated solar panel, general purpose whole room lighting

“**S300**” – Approx. $20 retail

4-16 hrs of light per charge, 10x brighter than kerosene, separate solar panel, mobile phone charging capability, general purpose whole room lighting, four brightness settings

6.2.2 Other secondary questions

Phase I

- What is the free trial to paying customer conversion rate, and does the conversion rate differ for those referred by peers?
- Does the number and size of local solar vendors affect the impact of this program?
- Are local solar retailers interested in participating in a Lighting Global sponsored program that would enable them to increase sales by offering free trials and sending automated texts on the benefits of solar which also encourage peer adoption?
- Can we accurately model reported kerosene/battery expenditures based on survey information (e.g. household size, number of kerosene lamps and other light sources, etc.), so that we can send future participants messages with their estimated savings without collecting their detailed expenditure data?

Phase II

- What are the ongoing answers to the Phase I secondary questions?
- How does the number or rate of non-referred free-trial participants (primarily early adopters), correlate with the number or rate of peer-referred participants? i.e. is there a tipping point where peer-referrals will adequately catalyze adoption going forward?
- How do we attract the early adopters to participate in the free trial until we reach the hypothesized critical point of peer-driven adoption?
- How can we effectively recruit local solar retailers to participate in this program?

Phase III

- Do payment plans increase adoption of solar products among the poorest of the poor?
- Can we phase out the free trial and rely on text-based peer information sharing to drive adoption?
- Are the results of our Phase II evaluation generalizable to other countries and contexts?

6.2.3 Sample Size Calculations

All sample size calculations, including the equations and tables below come from [128].

The equation for calculating number of clusters per group for Phase I based on proportion accepting our offer with a clustered (two-level) random sample and a binary outcome is as follows:

$$J = 1 + \frac{(z_1 + z_2)^2 \left[\frac{\mu_0(1-\mu_0)}{n} + \frac{\mu_1(1-\mu_1)}{n} + k^2(\mu_0^2 + \mu_1^2)\right]}{(\mu_0 - \mu_1)^2}$$

Table 6.2: Variables used in the equation above.

α	Desired significance level
β	Desired power of the design
z_1	z-value corresponding to the desired significance level of the test
z_2	z-value corresponding to the desired power of the design
μ_1	True (population) proportion in the presence of the intervention
μ_0	True (population) proportion in the absence of the intervention
n	Number of individuals in each cluster
J	Number of clusters in each group
k	The coefficient of variation of true proportions between clusters within each group[5]

The equation for verifying the sample size calculated above will have adequate power to detect effects in lighting expenditures based on a clustered (two-level) random sample and continuous outcome is as follows:

$$J = \left\{\frac{1}{P\delta^2}\sigma_y^2 \frac{(t_1 + t_2)^2}{-\rho + 1}(-R^2 + 1)\left(\rho + \frac{1}{n}(-\rho + 1)\right)\right\}$$

Table 6.3: Variables used in the equation above.

δ	Minimum detectable effect
α	Desired significance level
β	Desired power of the design
t_1	t-value corresponding to the desired significance level of the test
t_2	t-value corresponding to the desired power of the design
σ_y	Standard deviation of the outcome variable
J	Number of clusters
ρ	Intra-cluster correlation coefficient
P	Proportion of individuals assigned to the treatment group
n	Number of individuals per cluster
R^2	Proportion of outcome variance explained by level 1 covariate(s)

The equation for calculating the necessary sample size for a simple (single-level) random sample with a continuous outcome will be used in Phase II, and is as follows:

$$\boldsymbol{n = \left\{ \frac{1}{P\delta^2} \sigma_y^2 \frac{(t_1 + t_2)^2}{-P + 1} \right\}}$$

Table 6.4: Variables used in the equation above.

δ	Minimum detectable effect
α	Desired significance level
β	Desired power of the design
t_1	t-value corresponding to the desired significance level of the test*
t_2	t-value corresponding to the desired power of the design*
σ_y	Standard deviation of the outcome variable
P	Proportion of the study that is randomly assigned to the treatment group
n	Sample size

6.2.4 Impact Estimation

Table 6.5: Additional impact estimation sources.

Economic	Mean	std. dev.	Source
Annual savings on lighting and phone charging per product			
Average of 3 experimental studies in SSA	12.56	6.72	Grimm 2014, Rom 2017, Aevarsdottir 2017
Results from 2067 household RCT in Tanzania	19.92		Aevarsdottir 2017
Average of 13 values from 8 sources	53.95	38.86	
Additional Income or Productivity			
Experimental results from Tanzania			
Increase in household income	25%		Aevarsdottir 2017
extra time spent earning money	19%		Aevarsdottir 2017
phone charging income per 1000 products	184		Aevarsdottir 2017
Job creation per million lanterns	17800		Mills 2016
Health			
Indoor Air Quality - PM2.5			
Before-after study of 20 households in Kenya (relative to kerosene light sources)			
children exposure	73% lower		Lam 2017
adult exposure	50% lower		Lam 2017
Main room concentration - 4 day average	61% lower		Lam 2017
Pupils room concentration - 4 day average	79% lower		Lam 2017
Kitchen concentration - 4 day average	4% lower	not significant	Lam 2017
88 households in Uganda			
solar households relative to kerosene open wick lamp households	39% lower		Muyanja 2016
solar households relative to kerosene hurricane lamp households	not significant		Muyanja 2016
2067 household RCT in Tanzania (sampling duration/averaging period not provided)	7.5% lower		Aevarsdottir 2017
Social			
Women's Empowerment			
Results from 2067 household RCT in Tanzania			
Women working outside the household	26% higher		Aevarsdottir 2017
Women earning income outside the household	16% higher		Aevarsdottir 2017

Environmental			
Black carbon emissions			
wick g BC/year	1344		Apple 2010, Mills & Jacobsen 2011, Lam 2012, Grimm 2014
hurricane g BC/year	177		Apple 2010, Mills & Jacobsen 2011, Lam 2012, Grimm 2014
CO2 emissions			
wick kg CO2/year	44		Apple 2010, Mills & Jacobsen 2011, Lam 2012, Grimm 2014
hurricane kg CO2/year	57		Apple 2010, Mills & Jacobsen 2011, Lam 2012, Grimm 2014
CO2 equivalent emissions (including black carbon and CO2)			
wick kg CO2e/year	941		Apple 2010, Mills & Jacobsen 2011, Lam 2012, Grimm 2014
hurricane kg CO2e/year	124		Apple 2010, Mills & Jacobsen 2011, Lam 2012, Grimm 2014

6.2.5 Seasonality

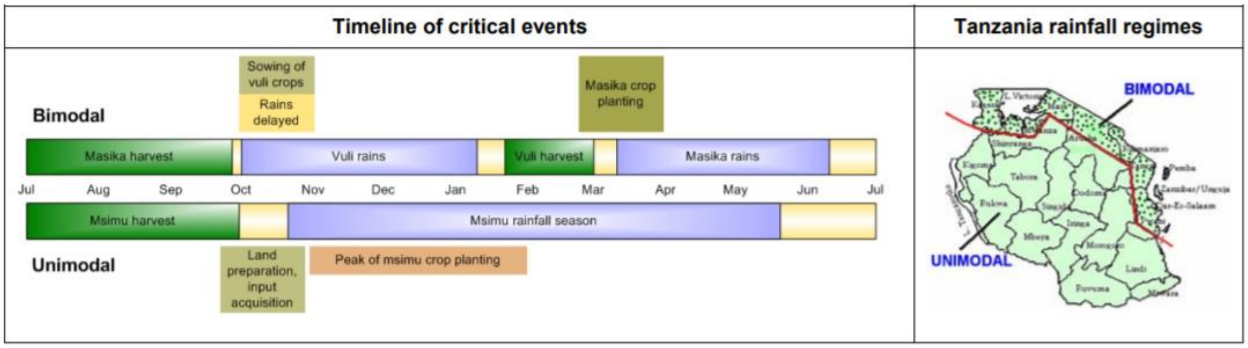

Figure 6.4: Seasonality of harvest in Tanzania [125].