OFF-GRID SOLAR ELECTRICITY ADOPTION IN NIGERIA

By

Obafemi Elegbede

A DISSERTATION

Submitted to
Michigan State University
in partial fulfilment of the requirements
for the degree of

Community Sustainability – Doctor of Philosophy

2019

ABSTRACT

OFF-GRID SOLAR ELECTRICITY ADOPTION IN NIGERIA

By

Obafemi Elegbede

One of the pressing challenges to economic development in sub-Saharan Africa (SSA) is access to electrical power. The region is endowed with natural resources that can meet this challenge. Yet, 620 million people in SSA lack access to electricity from a central grid, most of them living in rural areas. In Nigeria, there is a large gap in electricity access between rural and urban areas; only about 40 percent have access in rural areas as compared to almost 60 percent in urban areas. The Nigerian government has pursued a range of energy and development policies to increase access to electricity by 2020; their goal is to increase the amount of electricity from renewables to 2,000 megawatts. Despite such strategies and efforts, households continue to experience erratic supply of electricity and extended periods of black outs. Therefore, it remains critical to explore ways in which households can access electricity. The following dissertation is divided into three empirical studies. In the first study, a descriptive method is used to provide several insights on energy poverty in the Nigerian context, by examining the sources, expenditures, and challenges of access to energy. In the second study, discrete choice experiments (DCEs) are used to estimate the demand for off-grid solar electricity. In the final study, results from the descriptive method and DCEs are integrated into a system dynamics model (SDM) to simulate drivers of adoption for off-grid solar electricity over time. Findings from the first study indicate that as income increases, households consume more fuelwood and charcoal, are more dependent on petrol-powered generators for electricity, expressed interest in alternative sources of electricity, specifically off-grid solar electricity. DCE findings highlight tradeoffs households are willing to make to adopt this type of electricity. Finally, adjustment of prices, market access, and

consumer preference parameters in the SDM underline several policies that can encourage or suppress off-grid solar electricity adoption.

This dissertation is dedicated
To my wife for her support,
Dr. Jennifer Elegbede
To my sister
Tolu Haley
To my support group
Chiamaka Adeniran, Obafemi Osunfisan
To my Parents
To my Family
Above all Almighty God

ACKNOWLEDGEMENTS

First and foremost, I would like to thank God. Without my faith, I don't think I would have made it this far. To my wife for her support, thank you for everything. To my sister Tolu Haley, that fought by side for 20 years and still fighting thanks. To Obafemi Osunfisan and Chiamaka Adeniran my support system through the years, thank you for believing in me. To Dr. Cecelia Rouse thank you for meeting with me and encouraging me to go to grad school. To Dr. Lisa Cook thank you for all the meetings, you are the inspiration and role model that drove me through graduate school. I still want to be like you when I grow up. To Dr. Micheal Olabisi and Dr. Laura Olabisi, thanks for taking chance on me and supporting my matriculation in CSUS. For Dr. John Kerr, a big thanks for having unlimited confidence in me, spending countless of hours mentoring, training, and encouraging me that this was possible, even when I thought not. I hope to continue your legacy in excellence and mentoring. To Dr. Pero Dagbovie thanks for supporting when the lights went dim. To the director of AGEP, Mr. Steven Thomas, thank you for always listening and encouraging me through this journey. My research assistant in the field, Mr. Oluwasina Babarinde thank you for supporting the research. And to my parents, family and friends thank you. Finally, I would like to thank CSUS family and mentors for all the support they provided. I dedicate this dissertation to underrepresented groups and programs that support diversity, American Economic Association summer program (AEASP), Minorities in Agriculture, Natural Resources and Related Sciences (MANRRS), Alliances for Graduate Education and the Professoriate (AGEP) without your support for diversity I would not be here.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Introduction

Energy deficit is a major development problem facing African households. Only about 71% have access to clean energy sources, additionally only about 52% have access to electricity. As the population continues to grow, energy demands will continue to rise and needs to meet the demand will be critical (International Energy Agency, 2017). The situation is similar in Nigeria, IEA reported that 94% of households do not have access to clean energy and only 61% have access to electricity. Most of the people affected live in rural households; only 40% in rural areas have access to electricity as compared to 60 % in urban areas. There are challenges with the generation and transmission of electricity, for instance the grid only generates close to 50% of the capacity and about 45% of electricity generated is lost during transmission (Nigerian Electricity Regulatory Commission, 2018).

The Nigerian government has taken steps to improve electricity access by investing in power plants, and by installing wind and solar energy in some communities (Nigerian Electricity Regulatory Commission,2018). The Nigerian Government's target is to achieve 75% access to electricity by 2020 by connecting an average of 1.5 million households annually through grid extension as well as non-grid solutions using renewable energy like solar and wind (Rural Electrification Agency, 2018). But with population at 166 million and about 90 million without access, they are not installing or generating enough energy to meet the needs of people, because of several factors, including transmission infrastructural deficits (IEA, 2017).   Several explanations for the challenges in solving the electricity crisis are the absence of effective institutional and legislative mechanisms, corruption in leadership, and inadequate human resources (Aliyu, Ramli, & Saleh, 2013). Due to infrastructural deficit some of the rural households are not connected to the grid because they can't afford it (Sambo, 2008). The gap between demand and supply for electricity is high and it will continue to expand as population grows

(Sambo, 2008). With poverty levels at 86%, it is critical their electricity demands are met to contribute to the development of the country (World Bank, 2017).

The discussion above does not take into consideration poverty levels, household electricity needs and preferences, it only covers the institutional challenges of meeting the demands. There is need for rigorous empirical investigation to understand what constraints households are facing, what their needs are and how they can be met.

This dissertation seeks to address this need. The dissertation pursues three overarching objectives. The first is to understand households' energy demands, sources, challenges and constraints. The second is to understand what attributes households are looking for in off-grid solar electricity and their willingness to pay. The third is to understand the drivers of off-grid solar electricity adoption over time. These objectives are undertaken through three distinct related studies.

The first study (Chapter 1) is entitled "Household Energy Poverty in Nigeria: Sources, Expenditures and Challenges." In Nigeria about 86% of the population live in poverty, they also suffer from energy poverty because they lack access to electricity, and are heavily dependent on biomass to meet their energy needs(International Energy Agency, 2017; World Bank, 2017). The study is focused on the relationship between household income and primary energy sources, electricity use, and energy expenditure. The study uses a survey that was carried out at Idagba-Olorunsogo community in Ayetoro, Yewa north local government, Ogun State, southwest Nigeria in 2017. The study sample consisted of 120 randomly selected respondents. Descriptive and Chi-square statistical tests are conducted to determine relationships between variables.

The study yielded three key results. First there was a strong connection between household income and the type of energy sources. Low income households were more dependent on biomass. Overall, households had limited access to cleaner energy sources like liquid petroleum gas (LPG). Second, there was a strong relationship between income and the appliances households use. To meet their needs households only receive an average of two hours of electricity from the grid and supply is intermittent. So, some households use petrol-powered generators to meet their needs. Third, as income increases household consumption of charcoal increases, along with expenditures on electricity, while use of kerosene decreases. These results indicate that all income level households experience limited access to electricity and clean energy sources. They also demonstrate households' need for alternative energy sources to meet their electricity needs.

The second study (Chapter 2) is entitled "Estimating Demand for Off-Grid Solar Electricity in Households in Nigeria Using Choice Experiments." Building on the insights from the first study, a potential solution is the use of off-grid solar electricity to meet residents' needs. We can expect that households' perceptions, income level, and preferences about technology bear on their decisions to adopt off-grid solar electricity. The study split off-grid solar electricity into two technologies: Solar chargers and Photo Voltaic (PV) systems to reflect different markets. The PV systems consist of a solar panel, inverter, controller and battery. The study is focused on the tradeoffs households may make in adopting each technology.

The study used data derived from choice experiments and household surveys conducted with adult respondents in four different communities in Ayetoro, Yewa north local government, Ogun State, southwest Nigeria. These communities are Idagba-Olorunsogo, Oke Oyinbo, Oke Joga, and Saala. Both surveys for PV systems and solar chargers were conducted in April-May 2018: 300 surveys were collected for solar charger and 313 for PV systems. The relationship between households' preferences and off-grid solar electricity were analyzed using random parameter logit model. The model was used to estimate the demand of individual characteristics from off-grid solar electricity.

Results show that households were more trusting of PV systems than solar chargers and expressed concerns over the quality of both products. They were willing to pay more for quality and wanted to own PV systems individually rather than as a community. The results from the model showed households were willing to pay more for PV systems and solar chargers made in the USA relative to China. They attributed different quality to each country. Other attributes like the amount of power generated and hours of power provided were not important for solar chargers. Attributes like the number of hours the system can be used was not an important attribute for PV systems. Energy savings was an important attribute; the results showed households were not willing to pay more to save costs on petrol. This result was not consistent with our expectation and data could not explain the finding. A hypothesis can be that petrol is heavily subsidized in Nigeria. The amount of power generated from PV systems was an important attribute and results indicated households were not willing to pay more. It is consistent with what households expressed in the survey that people might want less to power until they can trust the technology.

The third study (Chapter 3) is entitled "Systems Dynamics Simulation for Off-Grid Solar Electricity Adoption in Nigeria." Despite the benefits of off-grid solar electricity there is low adoption in Nigeria. The challenge is to understand how, if, and when a technology will be adopted by end users and understanding the mechanisms behind off-grid solar electricity adoption. This study assesses the impact of lowering price on adoption behavior. It also seeks to understand the effect of off-grid solar electricity attributes on adoption. Another objective of the study is to comprehend the effect of the level of trust, word of mouth and product life on dis-adoption. It also provides an understanding on how market access affects adoption behavior.

The study used insights from the previous two studies. The insights contributed to systems analysis to gain knowledge on the feedback processes and long-term dynamics of the households and off-grid solar electricity systems in Nigeria.

Four key results have emerged from the third study. First, the government policies that support off-grid technology price reduction will contribute to increased adoption over time. Second, increased trust in technology drives adoption. Third, better product life suggests a profound impact on adoption. Finally, market access had the strongest impact on adoption. These results suggest that mechanisms like reduction in import taxes, price subsidies and stronger regulations on product quality, could greatly improve adoption of off-grid solar electricity in Nigeria.

REFERENCES

REFERENCES

Aliyu, A. S., Ramli, A. T., & Saleh, M. A. (2013). Nigeria electricity crisis: Power generation capacity expansion and environmental ramifications. *Energy*, *61*, 354–367. https://doi.org/10.1016/J.ENERGY.2013.09.011

International Energy Agency, I. (2017). *Energy Access Outlook 2017 (from Poverty to Prosperity)*. Retrieved fromhttp://www.iea.org/publications/freepublications/publication/WEO2017SpecialReport_EnergyAccessOutlook.pdf

Nigerian Electricity Regulatory Commission. (2018). Electricity: Generation, Transmission, Distribution and Market Financial. Retrieved March 6, 2018, from http://www.nercng.org

Rural Electrification Agency. (2018). Catalysing the off grid market to increase electricity access to rural and underserved communities through public & private sector engagement. Retrieved November 17, 2018, from http://rea.gov.ng/

World Bank. (2017). *Atlas of Sustainable Development Goals 2017: World Development Indicators*. https://doi.org/10.1596/978-1-4648-1080-0

CHAPTER 1: HOUSEHOLDS IN NIGERIA: ENERGY SOURCES, EXPENDITURES AND CHALLENGES

1.1 Introduction

The International Energy Agency (IEA) considers energy poverty as a lack of access to electricity and dependence on biomass for cooking. It is estimated that about 1.4 billion people are without electricity; of those, 99% are located in developing nations, with 44% being in Africa (International Energy Agency, 2017). As population grows, the demand for energy will follow, and energy poverty may increase as well (Kaygusuz, 2012). Recent analysis of poverty in Sub-Saharan Africa suggests that 41% of its population live in extreme poverty (World Bank, 2017), and that poverty is highest in rural areas. A majority of poor households find it challenging to meet their basic energy needs (World Bank, 2017). Poorer households tend to consume less energy, lack access to electricity or other clean energy sources, and depend heavily on biomass energy (International Energy Agency, 2017; Pachauri, Mueller, Kemmler, & Spreng, 2004).

Energy poverty also affects the social well-being of households. For instance, in developing countries women are largely responsible for cooking and spend an average of 1.4 hours per day collecting fuelwood (International Energy Agency, 2017). This means less time to spend with family, on income generating activities, or positive growth activities within the community (Ekholm, Krey, Pachauri, & Riahi, 2010). A study conducted in Nigeria found that people exposed to smoke and toxins from the use of fuelwood suffer from respiratory diseases (Richard, Benjamin, & Simon, 2009)

Energy is a necessity and improves quality of life by increasing the time children spend reading, allowing the preservation of food, and supporting small businesses (World Bank, 2017). Furthermore, the availability of energy contributes to productive agriculture and industry, which in turn reduces poverty (International Energy Agency, 2017). Kowsari et al., (2011) emphasize how critical energy is to development, particularly if it is reliable, accessible, and adequate (Kowsari & Zerriffi, 2011).

In oil-rich Nigeria—a top ten producer of crude oil—most people are paradoxically energy-poor (Shaaban & Petinrin, 2014). Sixty percent of the population (mainly urban households) have access to electricity, but the majority of rural households lack access. The country's infrastructure only provides 4,597 megawatts (MW) monthly, while the estimated demand is 28,000 MW (Nigerian Electricity Regulatory Commission, 2018; Sambo, 2008). The electricity provided is also intermittent. Power interruption to individual customers, on average, is about 1,460 hours per year (one-sixth of the year), compared to the United States where power is interrupted for about 1.3 hours per year (Oyedepo, 2012). Some households are dependent on biomass because they cannot afford diesel and are not connected to the grid. IEA (2017) reports about 90% of the energy used by households in Nigeria comes from biomass, and the majority of the population depends on it to meet their energy needs (Oyedepo, 2012).

One study of energy poverty in Nigeria attributed "corrupt and failed leadership" as the causes of the country's energy poverty (Sunday, 2011). For example, in 2006, the Nigerian government formed an agency called the Rural Electrification Agency (REA) to tackle electricity in rural areas. Due to governance issues the agency's leadership was removed in 2009 (Eleri, Ugwu, & Onuvae, 2012). Another study on energy poverty in Nigeria focused on energy consumption, using electricity as a proxy (Chidebell-Emordi, 2015). The study found that electricity cost was close to 25% of household income.

To tackle energy poverty in Nigeria, it is necessary to gain a greater understanding of people's basic energy needs, the sources of energy they rely on, and the constraints they face. Therefore, this study seeks to provide insights on energy poverty in the Nigerian context, by examining the sources, expenditures, and challenges of energy. The paper seeks to address the relationship between household income and primary energy sources, electricity use, and energy expenditure.

1.2 Analytical Framework

To understand energy poverty in the African context, we examine it from three perspectives used to capture energy poverty in households: access to energy, electricity use, and energy expenditure (Pachauri et al., 2004).

The first perspective is access to energy. This perspective gives an account of what energy sources respondents used and what they used them for, by income group. Access to energy also plays a role in how a household will make choices. For instance, a household that does not have access to gas will be less likely to purchase a gas stove. Alam et al. (1991) used access to electricity as an indicator of energy poverty with data from 112 countries (Alam, Bala, Huq, & Matin, 1991). In the Nigerian context, it will be useful to know data on households' access, infrastructure for electricity, and energy sources. This perspective focuses on the energy choices available to households.

The second perspective is electricity use. This perspective gives an assessment of what electrical appliances are used by income group, which is used to estimate people's consumption of electricity. It is critical to understand if households are meeting their basic energy needs as opposed to if they are experiencing energy poverty. Adeoti et al. (2001) used a similar approach in the assessment of domestic electricity consumption of Nigerian rural households. The study evaluated domestic energy consumption in a rural area, focusing on the amount of energy, duration of use, appliances, connectivity to the grid, and number of households. The study was able to determine the average daily use per household (Adeoti, Oyewole, & Adegboyega, 2001). The study found that there was a deficit in electricity supply but it can be met with solar photovoltaic-based electrification.

Under the final perspective, the focus is on measuring people's expenditure on energy, by income group. This perspective takes into consideration human behavior, income, prices and household energy expenditure. Studies of household energy use and poverty have been conducted in many Asian countries (most especially in India) and Sub-Saharan Africa. For example, as income increases, energy as a share of the budget decreases (Leach, 1987). Another study by Pachauri et al., (2004) took into account the time and transaction cost spent in acquiring fuel. They found energy costs are higher among poorer households because they spend more time collecting energy sources or more money per unit of energy consumed.

Finally, the basis of energy poverty for households is derived from the energy transition concept. As a household's income increases or as countries undergo economic growth, they tend to depend less on biomass and more on petroleum and electricity (Hiemstra-van der Horst & Hovorka, 2008). The notion of going from biomass to other forms of energy is modeled by the "energy ladder" (Hiemstra-van der Horst & Hovorka, 2008). The energy ladder model illustrates the relationship between income and energy with fuel switching. The model breaks down the relationship into three segments: the first segment includes households that are completely dependent on biomass. As income increases, the second segment denotes a switch from biomass to kerosene, and charcoal, and then a final phase is a switch to liquified petroleum gas (LPG) and electricity. However, fuel switching doesn't always occur as income increases; Heltberg (2004) reports that in rural areas as income increases, households adopt modern fuels but continue using fuelwood alongside modern fuels. Furthermore, research has found that rural households stack fuel sources as income increases, instead of switching (Masera, Saatkamp, & Kammen, 2000). For example, households choose to buy more fuelwood as income increases in addition to adopting cleaner energy sources. We will explore both energy stacking and switching here.

1.3 Data and Methods

Scoping interviews were conducted along with a survey designed to understand energy needs, energy sources, and rural electrification. The case study method identifies households' interaction with energy. As such, a survey was developed that combined structured and semi-structured questions. For more information about the survey see Appendix A. The survey collected data on household demographic and socioeconomic characteristics along with appliance ownership and energy use and expenditure. The data were collected using Nigerian naira then converted to US dollars.

The survey consisted of questions divided into sections on energy needs, energy sources and expenditure for lighting and cooking, electricity access and reliability, household demography, housing, employment and credit. The energy needs section contained questions on household appliances such as fridge, electric stove, gas stove, kerosene stove, GSM phone, television, and fan. The energy sources section focused on household costs, energy used and challenges. In the section on electricity, the goal was to understand fees, grid connection, reliability and perception of the electricity provider. Household demography provided information regarding age, sex, and household size. Households' financial and educational attributes were determined through inquiries on employment type, education, income, and access to informal credit.

Semi-structured questions in the survey focused on challenges and constraints that households faced in using different energy sources. These questions were designed to take an exploratory approach to encourage individuals to disclose information that may be omitted in a structured survey (Glesne, 2010). All the data were collected face-to-face with households. The information collected from the semi-structured questions generated a rich narrative to help foster a deeper exploratory understanding of the issues relating to energy poverty.

It is important to recognize that the data collected on energy use and energy expenditures are only approximate. However, the rough numbers generated in this paper are still sufficient to provide insight into energy access, use and expenditure in rural Nigeria, including the types of energy sources that different households use, and the variation across income groups.

The study was carried out at Idagba-Olorunsogo community in Ayetoro, Yewa north local government, Ogun State, southwest Nigeria (Figure 1.1). The community is also close to a state university and a federal government clinic, so the households interviewed had a blend of students, families and seasonal workers. The town is close to Benin, surrounded by forest. The community is also more of a peri-urban settlement. The surveys were conducted in English with two enumerators.

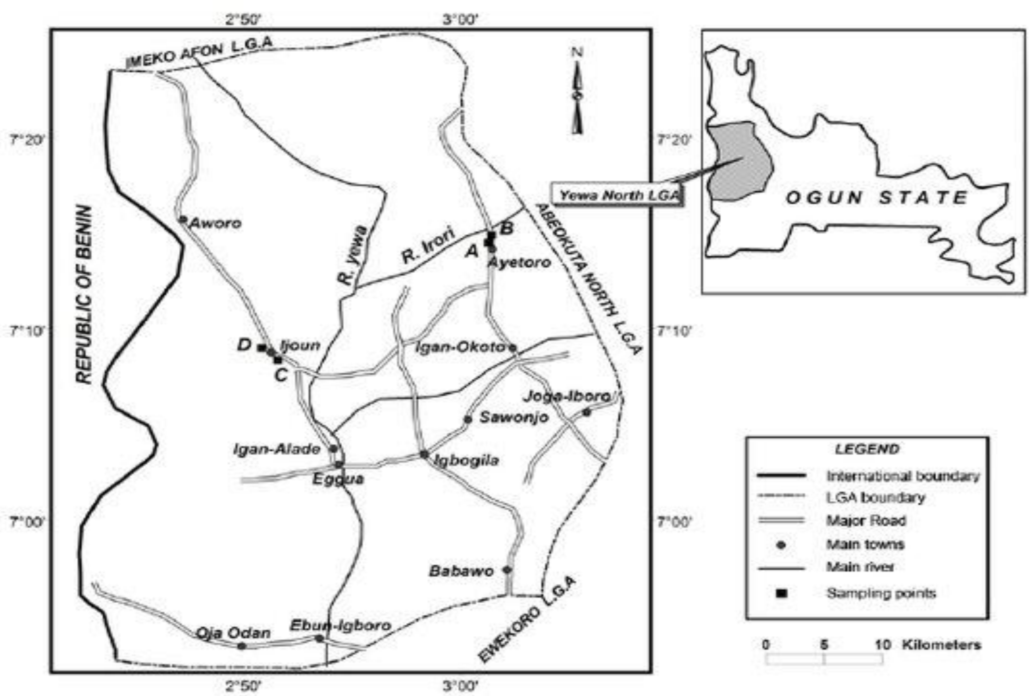

Figure 1.1: The map of Yewa north local government, Ogun State, southwest Nigeria (Salawu & Odaibo, 2014)

The town was chosen due to its variety of household energy sources. Some households of Ayetoro are connected to the electrical grid, while a clear majority of these same households also use biomass or kerosene as an energy source. Likewise, the town's clinic depends on the use of solar energy to power freezers for vaccinations. The study sample consisted of 120 randomly selected respondents. It consisted of traders, construction workers, students, government workers, teachers, retirees and business owners.

The data were analyzed using a descriptive method through the three perspectives (access to energy, energy use and energy expenditure) introduced above. In the three perspectives, the focus is on the energy a household needs for cooking and for operating large and small electrical appliances.

To better understand energy-use patterns we split respondents into three income groups, based on self-reported estimates. The groups are the average weekly income respondents reported: $0 - $14.16 (low income), $14.17 - $33.99 (middle income) and then above $33.99 for (high income). The low-income group consisted of 44 respondents, the middle-income group 36, and the high-income group 40. The groups were determined based on how the data was clustered.

We developed this classification system due to data limitations. The census data in Nigeria are aggregated to the national level and data identifying socio-economic status in the Ayetoro area do not exist. There is also a random pattern to housing development, with a mixture of residences with different socio-economic status and income levels. This facilitated diversity in the sample across income groups.

The data was analyzed with STATA statistical software, to determine relationships between independent variables like energy sources, electrical appliances, generators and respondent's income. Chi-square statistical tests were used to test if the relationships are statistically significant.

1.4 Results and Discussion

The survey sampled 120 respondents that included 57 males and 63 females, with an average age of 38. Most were employed. Their average household size was about five people with an average of three children per household. The results are organized around household energy access, electricity use, and energy expenditure, by income group. The access to energy perspective is separated into two sections: cooking fuels and electrical appliances. The electricity use perspective focuses on electricity demand, both from the grid and from generators. The energy expenditure focuses on cost of cooking fuels and electricity.

1.4.1 Access to Energy

This perspective provides a view on how different households access energy and the associated challenges and constraints.

1.4.1.1 Cooking fuel

For cooking, the main energy sources are charcoal, firewood, kerosene, liquid petroleum gas (LPG) and electricity, but there are challenges households face when using these energy sources. According to the survey, most households use kerosene and charcoal. About a quarter of the respondents reported they used liquid petroleum gas (LPG) in addition to kerosene and/or charcoal.

One of many challenges that rural households face is seasonality between Nigeria's rainy season and dry season. In figure 1.2 there is a 45% drop from dry season to rainy season in the use of fuelwood and charcoal. One of the major reasons for the drop is moisture from the rain, which affects how the biomass fuels burn. Also, most of the cooking is done outside due to the structure of most of the houses, so the rain deters cooking. On the contrary, the use of kerosene increases by 107% from dry to rainy season, and LPG use rises by 54%. To examine the relationship between income and fuel type, a chi-square (chi^2) test was used to determine the likelihood that the results occurred by chance. With energy sources used in rainy season as the dependent variable and household weekly income as the independent variable, household weekly income was found to be statistically significant. With energy sources used in the dry season and household weekly income, household weekly income was also found to be statistically significant. For more information about the results see Table 1.2 and 1.3 in Appendix.

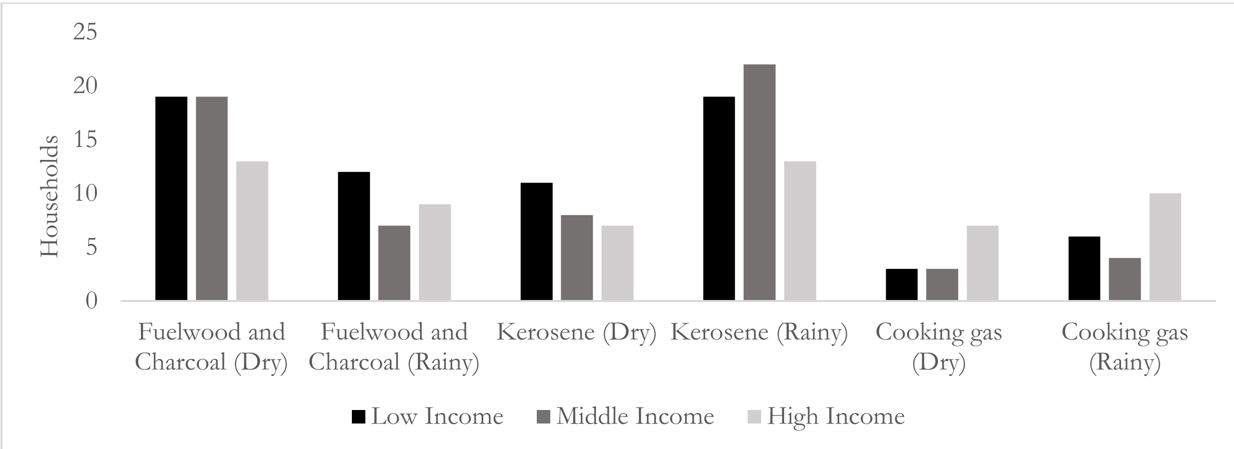

Figure 1.2: Seasonality and Energy Choices of Households

In the survey, 78% of the households that use charcoal and fuelwood purchase it from the market, while the remainder get their supplies from their farms, neighbors and the surrounding forest. Even though charcoal is popular with households, there are challenges in using it.

A respondent said:

> "It takes longer time to light up and cool down after use. Sometimes the quality of the purchased charcoal is poor, and it might not burn well due to moisture."

Another respondent said:

> "The smoke from the charcoal affects my eyes, breathing and also leaves odor on my clothing."

Households spend more time rearranging the charcoal and wood while cooking, fanning flames, and keeping their children away from the cooking.

In the survey, 89% of households that use kerosene purchase it from petrol stations, while the remainder purchase it from small shops owned by people in the community. Households with lower income are more likely to purchase from community members because it is available in smaller quantities for sale, as compared to petrol stations that only sell per liter. Based on conversations with respondents, most of the challenges associated with kerosene have to do with cost. Respondents indicated that they struggle to buy the quantity they need. Other challenges involve availability from the stations, which sometimes lack kerosene to sell; distance to the stations; and price fluctuations. Price fluctuations occur when there is lack of delivery from the national kerosene distributor. Respondents also complained about the quality of kerosene; it burns out very quickly and releases fumes during cooking. Some respondents expressed that it was used only on firewood and charcoal to accelerate the ignition process due to the moisture in the wood.

The next energy source is LPG, which 23% of households in the survey use for cooking. According to the survey, as income increases from middle to high income so does the number of households using LPG to fill their energy needs. Furthermore, more households use LPG in the rainy season; interestingly, higher-income households use LPG less in the dry season. It may be attributed to a stronger preference for charcoal. Advantages of LPG are efficiency, longer use and cooking indoors. Households have to be able to afford gas stoves as the price of stoves serves as a barrier to using LPG. Interestingly, among respondents in the lower income group that also use LPG, they were likely to be part of multiple-family households, allowing costs to be shared among them. The ability to share costs among households could mean greater adoption of other energy sources where cost is an issue. However, there are also other smaller forms of LPG stoves that can be used by low-income households that cannot share costs with others. For instance, some students reported using camping-style LPG stoves for cooking as they are more affordable and portable for their living arrangements.

There are other challenges associated with LPG. Unlike the kerosene and petrol that are sold at petrol stations, cooking gas is sold at depots. In this case, the depot is located 40 minutes from the town. The only cooking gas sold in town is 3 to 6 kg for a camping-style stove, as opposed to the larger size of 12.5 kgs. For LPG, access plays a critical role because even if households can afford it they may be hindered by its inaccessibility.

Finally, some households indicate that they use electricity to cook. In this case they are not referring to electrical stoves but hot plates. They are powered by electricity from the grid or generators. Some respondents complained about the sporadic electricity supply damaging their hot plates. Another challenge is buying petrol for the generator to use the hot plate; the cost of use is high given the inefficiency of hot plates in cooking.

1.4.1.2 Energy for large Electrical appliances

Interestingly, about 92% of the households are connected to the grid, yet close to 60% reported they have petrol-powered generators. (Detailed data on ownership of generators is presented later in the paper.) As income increases, the number of households that get most of their electricity from the grid decreases. Low- and middle-income households depend more on the grid than high income households because they less frequently own generators. The supply from the grid is unpredictable and unreliable. Some households are not connected to the grid for reasons like lack of payments, unaffordability, the house is not wired for electricity, or simply it is unreliable. Lack of reliability explains the demand for generators. Owning a generator comes with its own challenges, for instance durability, maintenance requirements, and security against theft. In fear of generators being stolen, some households use them indoors, which makes them susceptible to carbon monoxide poisoning or fires in the household. Also, the generators are not very efficient and consume a lot of petrol.

1.4.1.3 Energy for small Electrical Appliances

According to the survey, about 57% of respondents use batteries as a source of energy for small appliances. Small appliances reported by households include radios, battery powered lamps, flashlights, and rechargeable lamps. The majority of households use batteries because they are cheap and easily accessible. The batteries can be bought from community members that own small shops; in addition, batteries are readily sold in the local market. The challenge with batteries is that they cost more per unit of energy they provide.

For portable items like cellphones, some of the ways households meet their energy needs were very interesting. Households reported they charge their phones at retail outlets that sell energy. At the outlet, customers plug in their phones, paying a price of about 14 cents per phone. Households also reported the use of their neighbor's house, battery banks, and cars to charge phones. One respondent used his motorcycle to charge his phone, and another reported using a small solar set. Most households report using multiple ways to charge their cell phone.

1.4.2 Electricity Use

The second perspective focused on households' electricity demand from the grid and generators.

1.4.2.1 Electricity in Nigeria

The state of electricity in Nigeria is poor, with weak and outdated infrastructure to generate electricity. In the Nigerian Electricity Regulatory Commission report (NERC), only 49 percent of the capacity of the grid was used because of the limitation in gas supply and poor management (Nigerian Electricity Regulatory Commission (NERC), 2017). This leads to low supply of electricity that causes unplanned power outages that could last from several hours to days (Ikeme & Ebohon, 2005). Then the problem is heightened in rural areas due to limited infrastructure, which will be expensive to build. Evidence has indicated that the cost of electricity transmission from a central grid to rural areas is economically unattractive because rural areas have low load factors and require long distribution lines (Nouni, Mullick, & Kandpal, 2008).

In this section, the focus is on the number of appliances that households reported in the energy audit. From this information we estimate households' electricity demand, and also we explore how households are able to meet their electricity demand using petrol-powered generators. In the energy audit for each household conducted as part of the survey, most households reported the use of light bulbs, televisions, refrigerators, cell phones, hot plates, fans, radios, DVD player, electric irons, and boiling rings.

1.4.2.2 Electricity Demand

Households reported use of several appliances. Interestingly, in Figure 1.3, for smaller appliances like fans, mobile phones and light bulbs, the averages for low- and middle-income households are similar. In the sample as income rises, the average number of appliances increases. The chi-squared (chi^2) statistic was used to test the likelihood that the results occurred by chance. Testing each of the appliances as dependent variables and weekly income as an independent variable, the relationship between income and fans, fridges, televisions, and light bulbs was found to be statistically significant, while the relationship of weekly income with phones and radios was not statistically significant. For more information about the results see Table 1.4 in Appendix.

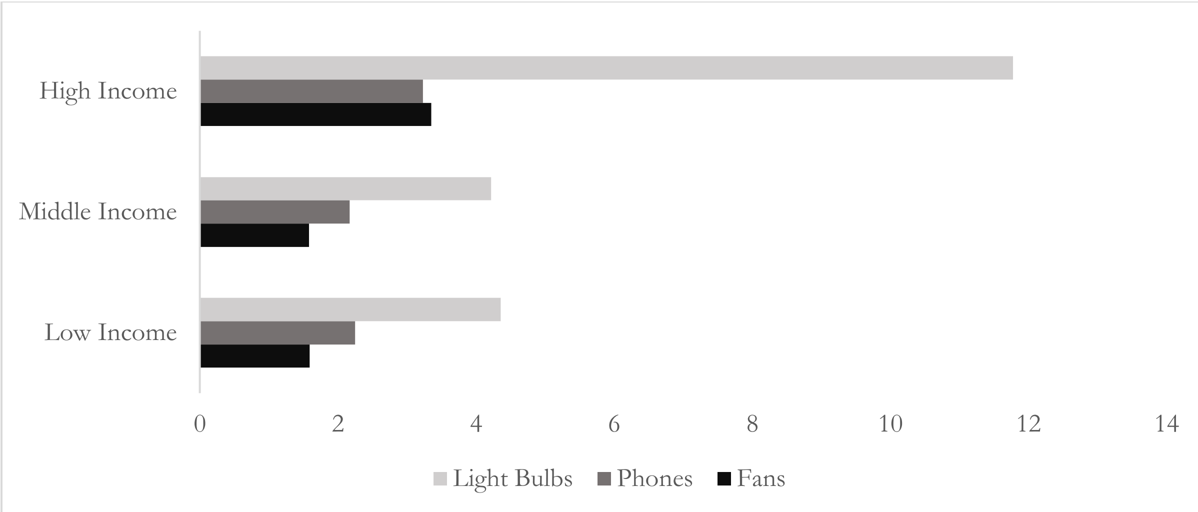

Figure 1.3: Average Number of Appliances

From Table 1 we can infer that refrigeration and lighting make up most of the electricity demand. This follows with most households' need for electricity to preserve food, and lights for safety and productivity. Table 1 is the estimated energy demand for electricity grouped by income level in kilowatt hours.

Table 1.1: Estimated energy demand for electricity by income level

Electrical Appliances (kWh)	Low Income	Middle Income	High Income
Fans	2.2	2.22	4.69
Televisions	0.84	0.996	1.204
Refrigerators	6.3	9.8	25.2
Light bulbs	7.33	7.09	19.78
Radios	0.008	0.006	0.011
Phones	0.189	0.182	0.271

*Hours per day used: we assume refrigerator used for 24 hours, light bulbs for 6 hours, cell phone charging for 3 hours, televisions for 6 hours, fans for 8 hours, radio for an hour. Then we derive weekly demand by multiplying by 7. The numbers in the table are inferred so statistical test was not conducted.

1.4.2.3 Electricity generation

The survey also collected information on the size of the generator to estimate how much power households are using to meet their electricity demand. The increase from middle to high income strongly correlates with the size of generators, and average time of use. As shown in figure 1.4, as income increases the size of generator also increases. Households with low income are the highest users of generators that are less than 2 kVA, while they are the lowest users of generators that are greater than 3.5 kVA. Low income households are more likely to use the 2 kVA generator because it is cheaper and provides enough power for light bulbs and cell phone charging. Also, they are more likely to use generators because of the low price of petrol. Figure 1.4 shows the type of generators households use per income level.

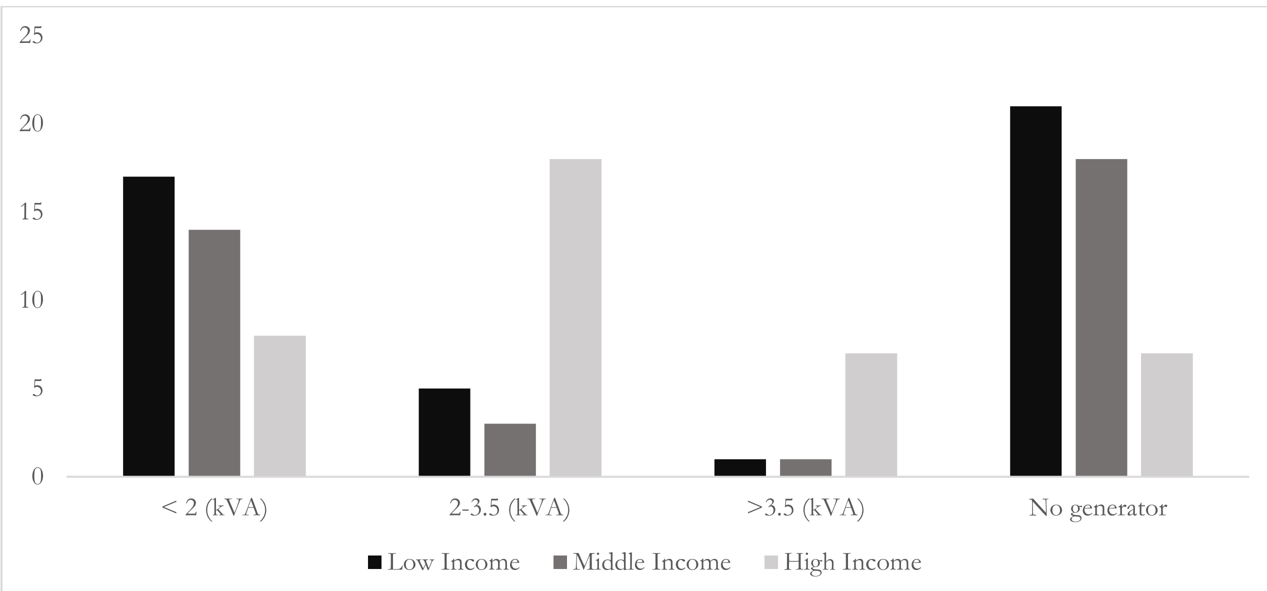

Figure 1.4: Types of Generators used by households

1.4.3 Energy Expenditure

The third perspective focused on the amount households spend on energy sources including electricity, by income level.

1.4.3.1 Cooking Fuel

As income increases, households increase their expenditure on energy sources. For kerosene it increases by 61% and 3% as income increases from low to middle income and middle to high income, respectively. For charcoal, the amount spent rises faster than kerosene, from low to middle 48% and from middle to high 103%. A slightly higher percentage of high-income households use kerosene as compared to low and middle-income households. From the energy ladder theory introduced above, households switch to cleaner energy sources as income rises (Hiemstra-van der Horst & Hovorka, 2008). Another theory introduced above is energy stacking, where households use more energy and more types of energy as income increases without necessarily giving up sources (Masera et al., 2000). In the results, households are spending more on charcoal as income increases while also using other energy sources. Studies in Mexico and rural India found similar results (Joon, Chandra, & Bhattacharya, 2009; Masera et al., 2000).

Interestingly, for higher-income households kerosene is an inferior good, because they switch to cleaner fuels, but they treat charcoal as a normal good. Overall, households on average spend more on charcoal than kerosene as shown in Figure 1.5.

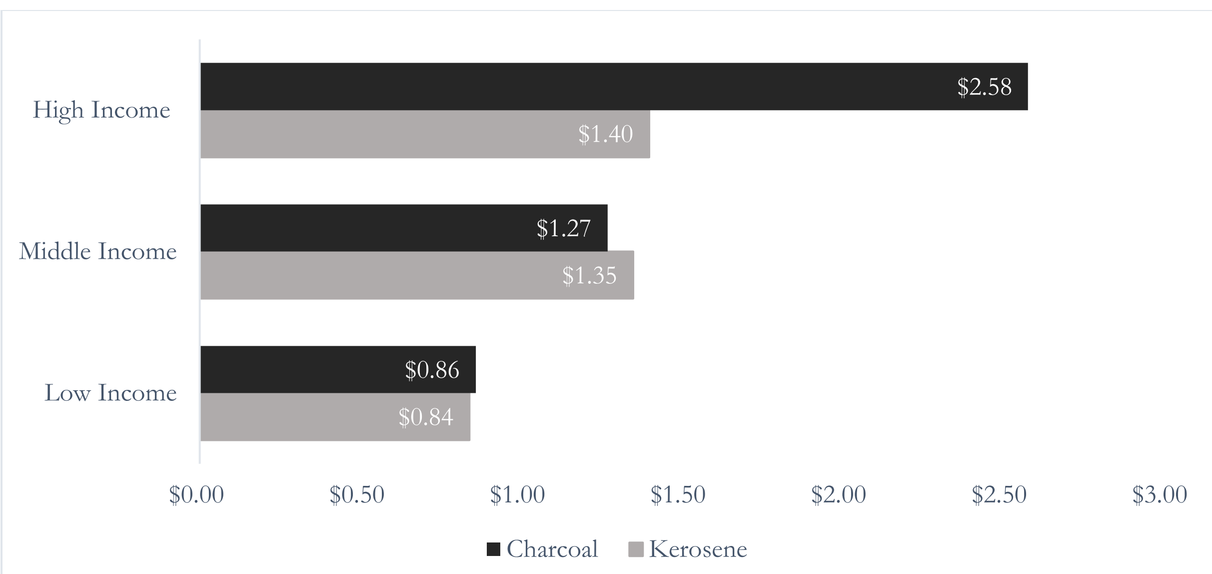

Figure 1.5: Expenditure on cooking fuel per week

1.4.3.2 Electricity

Examination of respondents' energy expenditure for appliances centers around the electricity bill from use of the grid and the cost of petrol for generators. This analysis requires caution in interpretation because the electricity bills are exorbitant relative to average incomes, yet we know that many people do not pay their bill at all (NERC 2018), and even most people who do pay do not pay the entire amount (Chidebell-Emordi, 2015). In particular, the NERC (2018) reports that only about 60% of people pay their bill. In addition, Chidebell-Emordi (2015) reports that as long as people pay part of their bill they will not be disconnected. The reason for this situation is that according to NERC (2018), only 44% of active customers are metered and the remainder received estimated bills. Customers complain that the bills are not accurate, particularly given their additional complaints of poor voltage, delayed connections, service interruptions, load shedding, etc.

It is with these caveats in mind that we can examine the survey results. From the electricity use perspective as shown in table 1.1 above, we can infer that higher-income households have higher energy demand because they use more appliances. Respondent households' electricity bills average about $8 every month. In figure 1.6, the increase in the electric bill from low income to middle income is about 95% while the increase from middle to high income is only about 8%. Although they were not specifically asked in the survey, some respondents indicated that they did not pay their bill, or they did not pay the entire amount. In general, they expressed frustration about the amount charged for electricity because they only get an average of 1-2 hours per day.

To meet the electricity deficit, households turn to petrol-powered generators. Figure 1.6 shows that the electricity bill is much higher than what respondents spend on petrol for their generators, despite experiencing a blackout for an average of 22-23 hours per day. The expenditure on petrol for generators reflects the energy demand per income level. As income increases from low to middle, petrol expenses increase by about 95%, and as income increase from middle to high income it increases by another 80%. The average time generators are used is about 5 hours. Despite the difficulties with the electricity billing data, we can see that energy expenditure rises by income group.

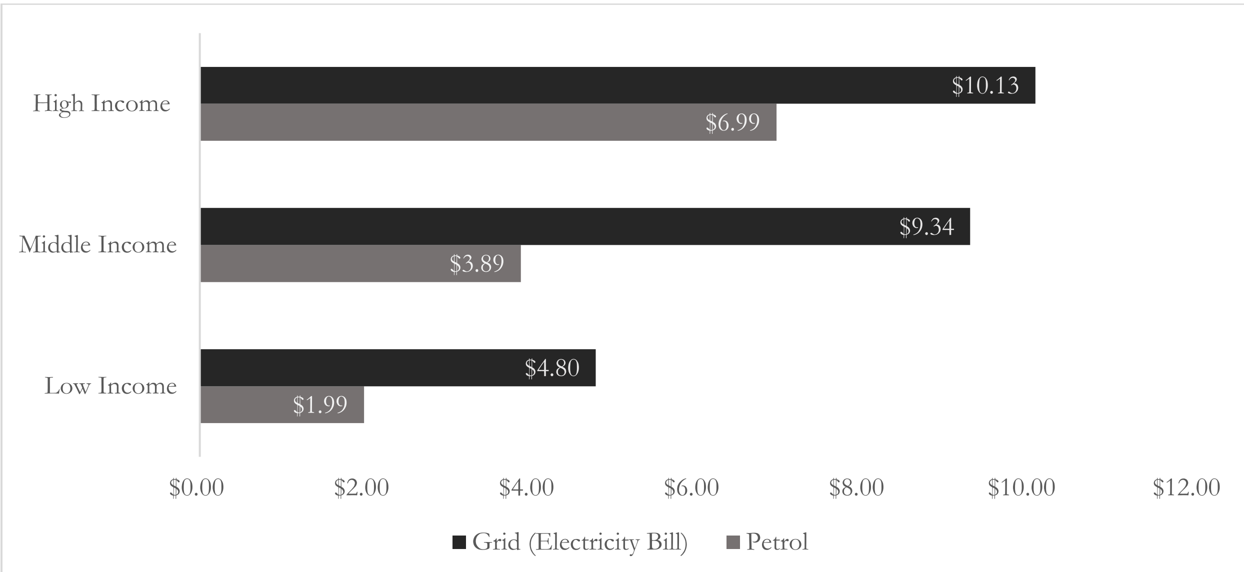

Figure 1.6: Expenses for electricity from the grid and for petrol for generators per week, by income group

1.5 Discussion

This study focuses on respondents' energy sources, expenditures and challenges to better understand energy poverty in households in Nigeria. As stated above, following the International Energy Agency (IEA 2017), we consider energy poverty as a lack of access to electricity and dependence on biomass for cooking. We used three perspectives to take an in-depth look at households and energy poverty: access to energy, electricity use, and energy expenditure.

The access to energy perspective suggested that households at every income level have access to charcoal and kerosene for cooking. The study showed the use of charcoal increases as income levels rise (Heltberg, 2004). Nevertheless, in the rainy season the use of charcoal faces challenges and isn't as effective due to moisture and caused less households to cook with charcoal. In reaction to the season, wealthier households use more cooking gas, however it is beyond the means for poor households. So, poor and middle-income households use more kerosene. Most households have need for electricity, but its access is limited by the unreliability of the grid, and whether households can afford to own and run a petrol-powered generator. As expected, generator ownership is closely related to income levels. Under the electricity use perspective, we see clearly that number of electrical appliances owned rises with income. Under the energy expenditure, we see that the electricity supply is inconsistent and low, along with exorbitant billing (Chidebell-Emordi, 2015). Households that own generators have to spend money on petrol, in addition some households spend money on batteries, while some pay small scale businesses for small amounts of electricity.

1.6 Conclusion

Overall, the energy access, electricity use, and expenditure mostly follow the expected relationships with income. The research also provides less support for the energy ladder theory because people aren't abandoning energy sources that that poorest people use. Households expressed frustration with the supply of electricity, and billing, they are also interested alternative sources of electricity such as solar.

The use of the three perspectives provided a more thorough understanding of household energy use in Nigeria. By incorporating access to energy, we were able to capture trends that correlated with income and also understand the barriers households face to access cleaner energy for cooking. The perspectives provided a realistic view of households' energy use. In addition, we were able to understand the electricity challenges households face. The interrelated perspectives provided a basis for household's energy use that can inform strategy to address energy poverty. It can also be used to inform implementation of using cleaner cooking fuels and electricity intervention.

APPENDICES

APPENDIX

APPENDIX A: Household Energy Survey

Do you consent to the collection of your information, and understand it will be kept confidential and used for research purposes? (Yes or No)

Name

Age

Sex (Male or Female)

Are you married? (Yes or No)

Are you head of household? (Yes or No)

Household size

Number of children

Are you employed? (Yes or No)

Type of Employment (Farming, Fishing, Construction, self-employed, professional services, other______)

How many years of school have you completed? (Primary school – 6 years, secondary/vocational school-12 years, polytechnic- 14 years, First degree- 16 years, other _______)

What is your income schedule? (Daily, weekly, monthly, seasonal, other______)

How much money comes into your household weekly (Income in Naira)? (6000-8000, 9000-12000, 13000-20000, Other _______)

Do use informal savings group or cooperative in the community? (Yes or No)

What is the status of your dwelling? (Owned, Rent, Provided by employer, Other_____)

If you rent, how much do you pay to rent per year?

If you had to rent your place how much would you receive per year?

Do you use space in the house for business? If so what activity? (Yes or No) if yes _______________

What type of roof material is used for your housing?

Please indicate the following items owned by this household (electronic items) and quantity? (Fridge, Air conditioner, Fan, Radio, Electric Stove, Television, GSM/Phone, Light Bulbs, Other_____)

How do you charge you cell-phone?

What is the main source of energy for lighting? (Kerosene, Electric grid, Generator, Other_____)

Do you use firewood?

Please explain use of firewood ______________

How do you obtain firewood? (Forrest, Purchased, Farm, other___________)

How much do you spend on firewood weekly?

What challenges do you face with the use of firewood? _____________

Do you use kerosene? (Yes or No)

Please explain use of kerosene

Where do you get kerosene from? (Gas station, Community member, Other______________)

How much do you spend on kerosene weekly? What are your challenges with Kerosene? _________

Are you the energy decision maker in household? (Yes or No)

What is the main source of your electricity supply? (Electric grid, Generator, Solar system, Other_____)

Are you connected to IBEDC (electrical grid)? (Yes or No)

If so, how many hours of electricity does your household use from the main public system, per day?

How frequently do you experience blackouts/No power in your area? (Everyday, several times a week, several times a month, others______________)

How long are the blackouts in your area?

What was the total cost per month for electricity in the household from IBEDC (electric grid)?

If you are not connected to public electricity, please specify the reason(s) for this lack of access, you can indicate more than one reason (Connection/wiring fee, Unaffordable, no need for electricity, dwelling inappropriate for connection, application pending, service too unreliable, disconnection from lack of payments, others please specify_____)

What source of energy do you use for cooking? (Charcoal, Firewood, Gas, Kerosene, electricity, others_)

Do you use a generator in this household? (Yes or No)

What is the size of the generator (kW)?

What amount of time during the day is the generator used (hours)? (2,4,6,8,10, other____)

What time of the day is the generator used? (Morning, Afternoon, Evening)

How much do you spend on your generator weekly?

What are the challenges with the generator?

During the rainy season what energy source do you use the most? (Fuelwood, Kerosene, Petrol, Other)

Please explain the reason

During the dry season what energy source do you use the most? (Fuelwood, Kerosene, Petrol, Other)

Please explain the reason

Are you familiar with solar systems? (Yes or No)

Can you please explain your understanding of solar systems?

Based on your understanding of solar systems would you be interested in installing one? why or why not?

Which household energy needs could solar systems help you to meet? why or why not?

Table 1.2: Number and percentage of households using different energy sources in the dry season, by income group

Energy sources[1]	Low Income	Middle Income	High Income	Total
Fuelwood and Charcoal	19 (43%)	19 (53%)	13 (33%)	51 (43%)
Kerosene	11 (25%)	8 (22%)	7 (18%)	26 (22%)
LPG	3 (7%)	3 (8%)	7 (18%)	13 (11%)
Combination of energy sources[2]	9 (20%)	5 (14%)	4 (10%)	18 (15%)
Petrol (Generator)	2 (5%)	1 (3%)	9 (23%)	12 (10%)
Total	44	36	40	120

[1] Pearson $chi^2(8) = 15.9014$ $P = 0.044$

[2] Households that reported the use of more than one energy source for cooking: kerosene, charcoal and fuelwood

Table 1.3: Number and percentage of households using different energy sources in the rainy season, by income group

Energy sources[1]	Low Income	Middle Income	High Income	Total
Fuelwood and Charcoal	12 (27%)	7 (19%)	9 (23%)	28 (23%)
Kerosene	19 (43%)	22 (61%)	13 (33%)	54 (45%)
LPG	6 (14%)	4 (11%)	10 (25%)	20 (17%)
Combination of energy sources[2]	6 (14%)	2 (6%)	0 (0%)	8 (7%)
Petrol	1 (2%)	1 (3%)	8 (20%)	10 (8%)
Total	44	36	40	120

[1] Pearson $chi^2(8) = 22.3568$ $P = 0.004$

[2] Households that reported the use of more than one energy source for cooking: kerosene, charcoal and fuelwood

Table 1.4: Average number of appliances used by income level

Electrical Appliances	Low Income	Middle Income	High Income
Fans[1]	1.59	1.58	3.35
Phones	2.25	2.17	3.23
Televisions[2]	0.59	0.89	1.08
Light Bulbs[3]	4.36	4.22	11.78
Radios	0.59	0.47	0.80
Refrigerators[4]	0.25	0.39	1.00

[1]Pearson chi^2 (20) = 30.9181 P = 0.056
[2]Pearson chi^2 (8) = 16.7096 P = 0.033
[3]Pearson chi^2 (50) = 72.3202 P = 0.021
[4]Pearson chi^2 (8) = 34.3170 P = 0.000

REFERENCES

REFERENCES

Adeoti, O., Oyewole, B. A., & Adegboyega, T. D. (2001). Solar photovoltaic-based home electrification system for rural development in Nigeria: domestic load assessment. *Renewable Energy*, *24*(1), 155–161. https://doi.org/10.1016/S0960-1481(00)00188-9

Alam, M. S., Bala, B. K., Huq, A. M. Z., & Matin, M. A. (1991). A model for the quality of life as a function of electrical energy consumption. *Energy*, *16*(4), 739–745. https://doi.org/10.1016/0360-5442(91)90023-F

Chidebell-Emordi, C. (2015). The African electricity deficit: Computing the minimum energy poverty line using field research in urban Nigeria. *Energy Research & Social Science*, *5*, 9–19. https://doi.org/10.1016/J.ERSS.2014.12.011

Ekholm, T., Krey, V., Pachauri, S., & Riahi, K. (2010). Determinants of household energy consumption in India. *Energy Policy*, *38*(10), 5696–5707. https://doi.org/10.1016/J.ENPOL.2010.05.017

Eleri, E. O., Ugwu, O., & Onuvae, P. (2012). *Expanding access to pro-poor energy services in Nigeria*. Retrieved from http://www.ecreee.org/sites/default/files/documents/basic_page/final-pro-poor-energy-access-paper-26-nov_nigeria.pdf

Glesne, C. (2010). *Becoming qualitative researchers.*

Heltberg, R. (2004). Fuel switching: Evidence from eight developing countries. *Energy Economics*, *26*(5), 869–887. https://doi.org/10.1016/j.eneco.2004.04.018

Hiemstra-van der Horst, G., & Hovorka, A. J. (2008). Reassessing the "energy ladder": Household energy use in Maun, Botswana. *Energy Policy*, *36*(9), 3333–3344. https://doi.org/10.1016/j.enpol.2008.05.006

Ikeme, J., & Ebohon, O. J. (2005). Nigeria's electric power sector reform: what should form the key objectives? *Energy Policy*, *33*(9), 1213–1221. https://doi.org/10.1016/J.ENPOL.2003.11.018

International Energy Agency, I. (2017). *Energy Access Outlook 2017 (from Poverty to Prosperity)*. Retrieved from http://www.iea.org/publications/freepublications/publication/WEO2017SpecialReport_EnergyAccessOutlook.pdf

Joon, V., Chandra, A., & Bhattacharya, M. (2009). Household energy consumption pattern and socio-cultural dimensions associated with it: A case study of rural Haryana, India. *Biomass and Bioenergy*, *33*(11), 1509–1512. https://doi.org/10.1016/j.biombioe.2009.07.016

Kaygusuz, K. (2012). Energy for sustainable development: A case of developing countries. *Renewable and Sustainable Energy Reviews*, *16*(2), 1116–1126. https://doi.org/10.1016/j.rser.2011.11.013

Kowsari, R., & Zerriffi, H. (2011). Three dimensional energy profile:. A conceptual framework for assessing household energy use. *Energy Policy*, *39*(12), 7505–7517. https://doi.org/10.1016/j.enpol.2011.06.030

Leach, G. (1987). *Household energy in South Asia*. Elsiever Applied Science Publishers Ltd., Amsterdam.

Masera, O. R., Saatkamp, B. D., & Kammen, D. M. (2000). From linear fuel switching to multiple cooking strategies: A critique and alternative to the energy ladder model. *World Development*, *28*(12), 2083–2103. https://doi.org/10.1016/S0305-750X(00)00076-0

Nigerian Electricity Regulatory Commission. (2018). Electricity: Generation, Transmission, Distribution and Market Financial. Retrieved March 6, 2018, from http://www.nercng.org

Nigerian Electricity Regulatory Commission (NERC). (2017). NERC Third Quarter Report 2017. Retrieved July 27, 2018, from http://www.nercng.org/index.php/component/remository/NERC-Reports/NERC-Third-Quarter-Report-2017/?Itemid=591

Nouni, M. R., Mullick, S. C., & Kandpal, T. C. (2008). Providing electricity access to remote areas in India: An approach towards identifying potential areas for decentralized electricity supply. *Renewable and Sustainable Energy Reviews*, *12*(5), 1187–1220. https://doi.org/10.1016/J.RSER.2007.01.008

Oyedepo, S. O. (2012). On energy for sustainable development in Nigeria. *Renewable and Sustainable Energy Reviews*, *16*(5), 2583–2598. https://doi.org/10.1016/j.rser.2012.02.010

Pachauri, S., Mueller, A., Kemmler, A., & Spreng, D. (2004). On measuring energy poverty in Indian households. *World Development*, *32*(12), 2083–2104. https://doi.org/10.1016/j.worlddev.2004.08.005

Richard, I., Benjamin, I., & Simon, E. (2009). Sustainable energy implementation in urban Nigeria. *Management Research and Practice*, *1*(1), 39. Retrieved from http://za2uf4ps7f.search.serialssolutions.com/?sid=google&auinit=R&aulast=Ingwe&atitle=Sustainable+energy+implementation+in+urban+Nigeria&title=Management+Research+and+Practice&volume=1&issue=1&date=2009&spage=39&issn=2067-2462

Salawu, O., & Odaibo, A. (2014). The bionomics and diversity of freshwater snails species in Yewa North, Ogun State, Southwestern Nigeria. *Helminthologia*, *51*(4), 337–344. https://doi.org/10.2478/s11687-014-0250-7

Sambo, A. (2008). Matching electricity supply with demand in Nigeria. *International Association for Energy Economics*, (4), 32–36. Retrieved from http://expertscolumn.com/content/matching-electricity-supply-demand-nigeria

Shaaban, M., & Petinrin, J. O. (2014). Renewable energy potentials in Nigeria: Meeting rural energy needs. *Renewable and Sustainable Energy Reviews*, *29*, 72–84. https://doi.org/10.1016/j.rser.2013.08.078

Sunday, M. (2011). Energy poverty and the leadership question in Nigeria: An overview and implication for the future. *Journal of Public Administration and Policy Research*, *3*(2), 48–51. Retrieved from http://www.academicjournals.org/jpapr

World Bank. (2017). *Atlas of Sustainable Development Goals 2017: World Development Indicators*. https://doi.org/10.1596/978-1-4648-1080-0

CHAPTER 2: ESTIMATING DEMAND FOR OFF-GRID SOLAR ELECTRICITY IN HOUSEHOLDS IN NIGERIA USING CHOICE EXPERIMENTS

2.1 Introduction

Electricity supply is a problem in Nigeria. The existing infrastructure only provides about 14 % of the estimated demand (Nigerian Electricity Regulatory Commission, 2018; Sambo, 2008). To fill the gap between supply and demand, households and businesses have resorted to the use of generators, kerosene lanterns, candles, and battery powered flashlights. Some households cannot meet their energy needs, so they are left in the dark. Furthermore, lack of energy supply leads to businesses operating at higher energy cost to meet their demands; it raises the cost of doing business and limits the number of new businesses entering the market. Therefore, there is a loss in economic opportunities and cost of doing business that is passed on to households (O. Oji et al., 2012).

According to the Nigerian electricity regulatory commission (NERC), on average for 2018 only about 49.5% of the capacity of the power plants are utilized, due to problems with gas supply, distribution and transmission. This inadequacy causes electricity to be rationed, inconsistent, and subject to partial and systematic collapse of the grid. For instance, in the third quarter of 2017, the country experienced one total system collapse and four partial system collapses (Ikeme & Ebohon, 2005; Nigerian Electricity Regulatory Commission (NERC), 2017). Adeoti et al. (2001) noted that the Nigerian government has sought to improve the power situation by updating the current infrastructure, extending grid lines to rural areas, and meeting electricity demand (Adeoti et al., 2001). The government invested over $16 billion from 1997-2007 to solve the power problems; however due to corruption and mismanagement of funds, the problems still persist (Aliyu et al., 2013). The NERC also generates revenue that can be used to address the power problems, but the revenue collected nationwide is only 55.3% of the total billed (Nigerian Electricity Regulatory Commission (NERC), 2017), and the majority of the revenue collected is used for administrative costs (Aliyu et al., 2013).

Therefore, there is a need to explore alternative ways of meeting the electricity needs of the Nigerian population that are cost effective, economically viable, consistent and environmentally feasible. One potential option that can be used to address the energy deficit in Nigeria is the use of solar energy, because of its enormous potential. For instance, in Nigeria, if 5% of the solar energy is converted, it can generate about 4.2×10^5 Gigawatt/hour (GW/h) of electricity, which would meet the country's demand and would be 26 times more than the electricity production from the grid (Ogunleye, 2011; Oyedepo, 2012). Off-grid options like photovoltaic (PV) systems and solar panel chargers are attractive options in addressing rural and urban energy needs because they can offer small amounts of electrical power that may potentially contribute to electrical appliances, agriculture, and general development (Adurodija, Asia, & Chendo, 1998). They also require low maintenance costs because they are durable and require no fuel. They can meet the basic energy needs of a household (Adeoti et al., 2001); however, there is no evidence of solar use as part of the household energy mix in Nigeria (Oladeji & Sule, 2016).

The main objective of this study is to assess the tradeoffs involved in using solar electricity from the perspective of Nigerian households. It uses choice experiments to measure households' preferences for solar electricity by exploring attributes rural households are looking for in photovoltaic (PV) systems and solar chargers. We quantify the various attributes of interest and estimate demand from individual characteristics of solar electricity. The study also investigates information effects on households' willingness to purchase solar electricity. Finally, the study provides an understanding of how households prefer to access solar electricity: individually, via group sharing, or as an energy provider who sells energy services to others.

2.2 Background on Solar Electricity

Nigeria receives about 3.5 to 7.0 kW h/m2/day of insolation because the country has different geographical parts. Converting 0.1% of solar irradiation to electricity would be more than enough to meet the energy demand of the people (Ogunleye, 2011). This translates to an enormous potential for solar technology (Okoro & Madueme, 2004). Despite this potential for solar, Nigerian households have been slow to adopt. In other parts of Africa, some countries have embraced solar energy, for instance 10% of electricity used by the rural population in Morocco comes from solar (Tsikalakis et al., 2011). In Sub-Saharan Africa, there are several countries that have had success with PV systems. For example, between 1960 and 2007, Kenya and Zimbabwe had strong PV dissemination; other countries like Uganda also followed similar patterns (Bawakyillenuo, 2012; Karakaya & Sriwannawit, 2015). In South Africa, a government program launched in 1999 installed solar home systems (Lemaire, 2011). Despite the enormous potential for solar, various factors affect adoption like households' preferences, architectural designs of homes, the state of electricity infrastructure, the electrical needs of households, the perception of the technology and cost.

This research will concentrate on solar electricity, specifically off-grid PV systems and solar panel chargers. PV systems consist of a solar panel, inverter, controller and battery. The panel converts sun energy (irradiation) to direct current (DC), which the inverter changes to alternating current (AC). Some of the energy can be stored in the battery to be used at night or during cloudy days. The controller is connected between the battery and inverter; it determines the flow of energy from the panel to the inverter or the battery (Figure 2.1). The process described is referred to as balance of system (BOS) (Ogunleye, 2011). Conversely, a solar panel charger is a portable panel that may only provide enough energy for a cell phone, radio, camera and/or rechargeable lamp.

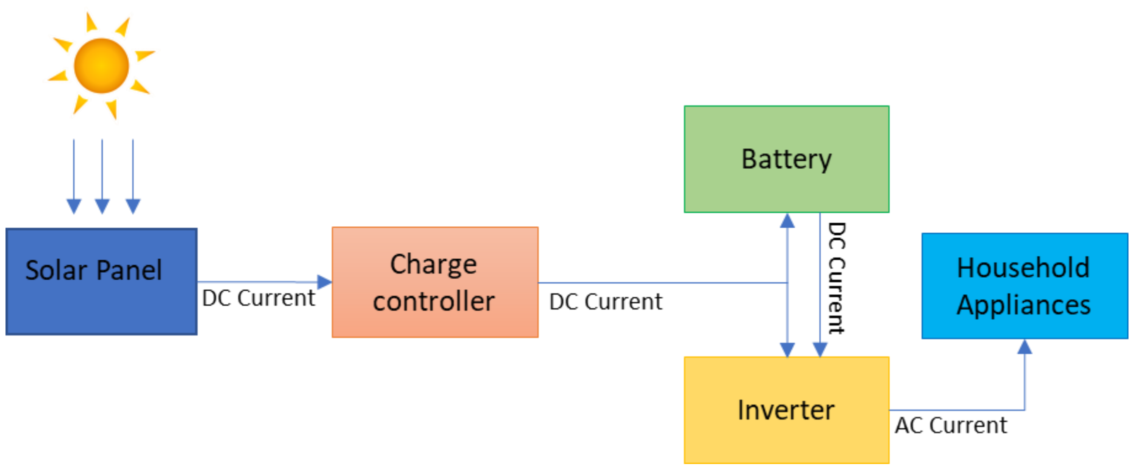

Figure 2.1: Converting solar energy to electricity in a photovoltaic (PV) system

Since off-grid PV system and solar panel chargers do not need to be connected to a grid but directly to households, less infrastructure is needed. Solar chargers can produce small amounts of electricity to households; the amount of electricity generated from the solar charger is enough to power and charge cell phones during the day, and small electronics like radios and rechargeable lamps that can be used in the evening. Even though the electricity supplied might be in small quantity it saves households time and money because they don't have to go out to charge their cell phones with street vendors. In addition, if households have solar chargers they don't have to depend on their neighbors who have generators for electricity or constantly buy batteries for their small electronics. For households with higher income and demand for power, they can opt for PV systems that have more power. It can save them from having to purchase generators and the gasoline to power them. Ogunleye et al., 2011 demonstrated that households in Nigeria that use solar electricity versus generators will save money in the long run and that it will have a positive environmental impact. Consequently, we estimate the household demand for electricity in the context of off-grid solar electricity in Nigeria.

2.3 Methods

2.3.1 Study Area

A previous survey in July 2017 covering the same population provided information about household energy use in the study area (Chapter 1). This information guides the design of the choice experiment presented in this paper. The previous survey included an energy audit of the amount of energy people use, its sources, and how much they spend. It also focused on people's experience with electricity from the grid and perceptions of solar technology.

The majority of respondents were connected to the electric grid. However, they only receive power three hours per day on average. They experience blackouts every day, and sometimes for days at a stretch. It was difficult to estimate the amount of time households had power because they only received power randomly throughout the day. In addition, when they had power, it was not always stable. The households experienced electrical damage to their appliances because of intermittent delivery from the grid.

Respondents expressed concerns with solar power. Some believed that when it rains, the solar power will not work. Another big issue is the amount of solar "technology" on the market that does not work efficiently or breaks down in a short amount of time. As a consequence, people are less trusting of technologies that run with solar or are connected with solar. However, most people expressed a willingness to adopt solar technology for several reasons. These include the constant electricity solar might provide for them to keep their children safe at night, the use of lights for their shops, refrigeration of food items, and if possible for cooking. Student respondents said that they need electricity to study at night and when they are at home. They expressed a need for off-grid solar electricity that can be mobile and taken with them because they move frequently. Overall, people expressed willingness to adopt solar electricity if it is available, affordable, and properly explained.

2.3.2 Sampling

The data used in this study are derived from a household survey conducted with adult respondents in four different communities in Ayetoro, Yewa north local government, Ogun State, southwest Nigeria. These communities are Idagba-Olorunsogo, Oke Oyinbo, Oke Joga, and Saala. The community is also close to a state university and a federal government clinic, so the households interviewed had a blend of students, families and seasonal workers. The households were interviewed between April-May 2018; the sample consisted of randomly selected respondents.

2.3.3 Modeling preferences for off-grid solar electricity using choice experiments

The theoretical foundation of the study is based on Lancaster consumer theory, which provides the basis for discrete choice experiments (Lancaster, 1966). This approach assumes that utility is derived from the properties and characteristics of a good, and it assumes the consumption of a good as an activity that produces an output that is a collection of characteristics (Lancaster, 1996). The good in this instance is off-grid solar electricity. The good possesses energy characteristics, and environmentally friendly characteristics. This approach allows allocating the collection of characteristics with the use of off-grid solar electricity. This contributes to the analysis when trying to distinguish various consumers' reactions to prices, attributes, and applicability (Lancaster, 1996).

Choice experiments (CE) are used to understand how decision makers will hypothetically make choices to adopt new technologies. In this instance, the focus is on how consumers will choose between technologies that generate solar electricity. CE is grounded in consumer demand theory, and the assumption is that the decision makers are rational, and they aim to derive satisfaction or utility from their choices (Mankiw, 2008). Here, utility is defined as the level of happiness a person derives from his or her circumstances; it is a measurement of well-being (Mankiw, 2008). It is also assumed that the decision-makers aim to derive optimal satisfaction. Therefore, the decision makers seek to maximize their utility, with the assumption that they will always choose the most preferred good that is affordable (Varian, 1992).

In choice experiments, households are presented with sets of alternative combinations of attributes of off-grid solar electricity, and they are asked to choose their most preferred alternative. The data from the experiments reveal the trade-offs households are willing to make between attributes of off-grid solar electricity. The choices presented to households are modelled as a function of the attributes using random utility theory, based on individuals making choices on characteristics randomly (Scarpa & Willis, 2010).

Theoretically, consumers are assumed to maximize utility resultant from their decisions. The utility from individual choices is derived from two parts. The first part is the explainable variable that comprises the attributes of the good and the characteristics of the individual. These will be classified as Vij, where V is the variable, i is the individual and j is the choice (Lancsar & Louviere, 2008). The second part is the non-explainable variable, unobserved attributes, measurement error or random component, classified as εij. Therefore, the utility (U) an individual gets from choices can be expressed in equation form as:

$Uij = Vij + \varepsilon ij$ *(Equation 1)*

Vij is the systematic component that is a function of goods/service and characteristics, it is modeled as:

$Vij = X`ij \beta + Z`i \gamma$ *(Equation 2)*

Where $X`$ is a vector of choice experiment attributes and socio-economic characteristics; β is the coefficient to be estimated and corresponding parameter for the $X`$ vector; $Z`$ is a vector of characteristics of individual $i$; and γ is the coefficient to be estimated and corresponding parameter for $Z`$ (Bennett & Birol, 2010; Lancsar & Louviere, 2008). Utility is comprised of observed and unobserved consumer satisfaction; it is a latent variable. Hence, it is assumed that an individual will make a choice if, and only if, their utility from that choice is higher than utility from other choices in a set of J alternatives (Bennett & Birol, 2010; Lancsar & Louviere, 2008). The probability P of the choice being 1 that maximizes utility can be expressed as:

$P(Yi = 1) = P(Ui_1 > Uij)$

$= P(Vi_1 + \varepsilon i_1 > Vij + \varepsilon ij)$ (* Note $Uij = Vij + \varepsilon ij$)

$= P(Vi_1 - Vij > \varepsilon ij - \varepsilon i_1)$ $(j \neq 1)$

Estimable choice models are derived assuming the errors are independently and identically distributed (IID). However, where an individual is allowed to make a choice given alternatives to choose from since households make repeated choices, the assumption of independence may be violated, since the choices might be correlated. Also, households are a heterogenous group whose preferences for off-grid solar electricity characteristics may also be heterogenous.

Therefore, the error term can be specified as

$\varepsilon ij = uij + vij$; $uij \sim N(0, \sigma 2)$, $vij \sim N(0, \sigma 2)$

where the u is the unobservable effects and v denotes the remainder disturbance; both being normally distributed (Bennett & Birol, 2010). To evaluate the heterogeneity, the use of mixed logit model, also called random parameters logit (RPL), is used (Hensher, Rose, & Greene, 2015). This choice modeling allows for the IID assumptions to be relaxed and considers different decision making of households.

2.3.4 Selection of Attributes

Based on the information presented above regarding the study area, the following attributes were selected for use in the choice experiment: price, hours, power, energy savings, and country of manufacture. The price of off-grid solar electricity is a concern in Nigeria as elsewhere (Adurodija, Asia, & Chendo, 1998). Though the price has dropped over the years, compared to other energy sources the cost of off-grid solar electricity is generally higher (Kabir, Kumar, Kumar, Adelodun, & Kim, 2018; Sarzynski, Larrieu, & Shrimali, 2012). Even though prices are dropping, households in Nigeria might not be able to afford PV systems, especially households in rural areas. In addition, the cost of installation of PV systems is also still relatively high, contributing to the economic affordability concerns (Karakaya & Sriwannawit, 2015). Hence, the research looks at two kinds of systems: PV systems and solar chargers. The price range used in the experiment for solar charger and PV systems were determined from market and online prices in Nigeria (Jumia Nigeria, 2018).

The price coefficient after analysis of choice experiment data tend to be negative, as a fundamental tenet of economic theory: given two otherwise equal choices, people will choose the one that is less expensive. However, literature in psychology shows that this is not always the case – that people often assume that a higher price means higher quality, and so therefore they choose the more expensive product in the absence of other information (Blood, Zatorre, Shiv, & Rangel, 2008; Smith & Broome, 1966; Zeithaml, 1988). Other studies also confirm that when consumers that do not have enough information on a product and cost to access information is also high, they will infer that a higher priced product is of higher quality (Bagwell & Riordan, 1991; Chan & Leland, 1982). This will be further addressed later in the discussion section.

Based on the off-grid technology prices and specifications we were able to estimate the number of hours the technology can be used for. For the solar chargers we explained to the respondents they can be used only during certain hours of the day, specifically during the day time. For PV systems we explained that they can be used longer depending on the size of battery and the size of panel. The hours were also informed by the average amount of time households got electricity from the grid. We wanted to explore the tradeoffs between current grid and off-grid solar electricity.

The attribute of power demonstrates the amount of wattage households can get from off-grid solar electricity. Since it will be difficult for households to understand power in wattages; pictures were used to depict the number of appliances as a proxy for power (see figure 2 for example). More appliances imply a more powerful system. The appliances were picked based on the energy audit conducted (Chapter 1), so that it corresponded with what households were familiar with.

The attribute energy savings is only in the PV system choice experiment, because we inferred that people that can afford PV systems are more likely to own generators. So, the tradeoff was between the cost of fuel for generators and use of PV system. Energy savings was based off the amount of fuel spent monthly; the range was determined from the energy survey (Chapter 1).
The final attribute for both experiments was the country in which off-grid solar technology was manufactured. From the previous energy survey, respondents expressed a lack of trust in solar technology. Most of the solar technology in the market was from China and is considered to be of lower quality. The United States was picked as an alternative country as a proxy for trust, to identify a price premium that people would be willing to pay for products they trust more. (See Tables 1 and 2). It is common knowledge in Nigeria that people perceive things from the USA to be of better quality, and they expressed that in the energy survey.

Table 2.1: Attributes and Attribute Levels in the Choice Experiments for PV systems

No	Attributes	Description	Attribute Levels
1	Price	Initial Investment (Upfront cost)	\$254.96, \$362.61, \$566.57
2	Energy savings	Monthly Energy savings from petrol cost of generators	\$14.16, \$38.40, \$56.66
3	Hours	Amount of time in hours it can be used for	5, 9, 14
4	Power	Wattage of PV systems	300, 500, 600
5	Country	Country where product is manufactured	United States, China

Table 2.2: Attributes and Attribute Levels in the Choice Experiments for Solar Chargers

No	Attributes	Description	Attribute Levels
1	Price	Initial Investment (Upfront cost)	\$28.33, \$39.66, \$53.82
2	Hours	Amount of time in hours it can be used for	2, 3, 5
3	Power	Wattage for solar chargers	3, 10, 15
4	Country	Country where product is manufactured	United States, China

2.3.5 Design of Choice Sets

For the experimental design, a set of profiles were constructed, and we used Ngene software to create orthogonal design with attributes and levels (Lancsar & Louviere, 2008; Ortega, Waldman, Richardson, Clay, & Snapp, 2016). For each product, the design considered attributes and their various levels. For the first product, PV systems, there are five attributes considered: four attributes with three levels and one attribute with two levels. This gives 4^3x1^2 (=64) possible profiles. For the second product, solar chargers, there are four attributes considered: three attributes with three levels and one attribute with two levels. This gives 3^3x1^2 (=27) possible profiles. For each product, a total of 18 choice tasks were generated and blocked into 3 groups of 6 choice scenarios. Respondents were only presented 6 scenarios instead of 18, to avoid fatigue and get better data. An option to opt out was available to respondents for each choice task (see Figure 2.2 for an example). The opt-out option is for respondents not interested in acquiring off-grid solar electricity. A booklet was created for each block, each containing 6 choice sets. The choice tasks were demonstrated and presented to households. A trial run was conducted to ensure the tasks were applicable to the respondents.

Choice 6	Option A	Option B	Option C
Investment	₦90,056.97	₦128,081.10	Neither A nor B, I will not buy
Savings	₦13,563.65	₦20,013.45	
Hours	5	14	
Power/ Wattage	 500	 600	
Country	 CHINA	 USA	

Figure 2.2: Example of Choice Task for PV system

2.3.6 Data Collection and Questionnaire

The data was collected over a 5-week period in April-May 2018 by trained enumerators. The surveys were conducted in English with two enumerators. The survey instrument was subdivided into six sections. The first section was dedicated to the demographic information: age, marital status, occupation, income per week, house ownership. In the second section people were asked about various ways they access electricity to charge their cell phone and if they paid to charge their cell phones. The third section asked respondents about alternative ways they met their electricity needs and the cost associated with it. It investigated the use of generators and fuel spent per week to power them. The fourth section was devoted to the choice experiment. The six choice tasks were presented to the households after a detailed explanation of off-grid solar electricity, and the various attributes. Photographs of each attribute were presented to them; they had the option of opting out (not choosing any of the options) and they were asked their reasons for opting out. The fifth section explored acquisition of PV systems. Because PV systems are very expensive, we wanted to understand if they were willing to own the solar power system as a part of a group, individually or as an energy entrepreneur providing electricity to others. The sixth section was used to gauge the confidence of households in off-grid solar electricity; in particular we wanted to know how much households trusted the technology and the reasons for their trust or distrust. People were asked to state on a rating scale ranging from 1 (least confident) to 10 (completely confident), if off-grid solar electricity would work for them. This question was asked to get an insight on how people view solar technology and their experiences. The questionnaire for solar chargers did not include a section for the ownership because they are much cheaper and lower capacity – so much so that it is unlikely that people would own them in groups. The completion of the questionnaires took about 20 minutes. 613 completed questionnaires were collected from households; 300 questionnaires were for solar chargers and 313 for PV systems.

2.3.7 Estimation

The objective of the research is to understand households' preferences regarding off-grid solar electricity. In addition, we want to understand how much households are willing to pay to obtain a type of off-grid solar electricity. This leads to a measure that is referred to as willingness to pay (WTP). The measure is determined by the ratio of two parameter estimates of attributes obtained from the Random parameter Logit (RPL) models while holding all else constant (Hensher et al., 2015). The coefficients obtained from the RPL models represent households' preference or marginal utilities for each of the attributes (Waldman, Ortega, Richardson, & Snapp, 2017). The samples for both experiments for solar chargers and PV systems were analyzed with NLOGIT software. For the RPL model, we applied 1000 Halton draws to investigate the preference heterogeneity amongst households and the utility formula is applied to the model.

$$U(alt1) = \beta_{price}\,Price + \beta_{hours}\,Hours + \beta_{watts}\,Watts + \beta_{country}\,Country + \beta_{savings}\,Savings \quad (1)$$

$$U(alt2) = \beta_{price}\,Price + \beta_{hours}\,Hours + \beta_{watts}\,Watts + \beta_{country}\,Country + \beta_{savings}\,Savings \quad (2)$$

$$U(alt3) = Opt\ out \quad (3)$$

The utility formula for solar chargers does not include savings, since the experiment was not designed to explore tradeoffs between solar chargers and generators since they are not substitutes. Price is a continuous variable indicating the extra cost of acquiring PV systems or solar chargers. Hours is a continuous variable that indicates the number of hours a household can use the technology for. Watts is a continuous variable that indicates the amount of power households can get out of the PV systems or solar chargers. Country is a dummy variable indicating country of manufacture for the solar technology (value 1 United States, 0 China) and savings is a continuous variable that is related to the amount households will be saving in fuel cost if they adopt PV systems as opposed to using a generator. The last alternative is the utility for those that opted out.

2.4 Results

The results section will be in the order of summary statistics from the survey and the choice experiments results.

2.4.1 Summary Statistics

Table 3 describes the households in both surveys. In our surveys the majority of the respondents earned less than $14.16 per week, which is about $2 per day. Over 60% of the households were renting their home. Our average respondent was about 34 years of age with about 14 years of formal education. Close to half of the sample were between the age of 18-30, which is reflective of the young Nigerian population. A little over half of the respondents in both surveys were married (57.6%).

Table 2.3: Sample socio-economic characteristics

Characteristics	Solar Charger	PV systems
Married	179	165
Dwelling		
Rent	195	194
Own	117	106
Total	312	300
Weekly Income		
$0.00 - $14.16	123	113
$14.16 -$42.49	94	91
$42.49 -$70.82	58	57
Above $70.82	37	39
Total	312	300
Age		
18-30	145	149
31-40	62	56
41-50	70	67
51-77	35	28
Total	312	300

According to our results, the average confidence rating in the PV system survey was 7.5 out of 10 and solar charger was 7.1. People were particularly concerned about the guarantee on the product. They were willing to consider a product if it came with a warranty/certification. Most electronic products sold in the markets have a "no return" policy; therefore, consumers must perform as many tests as possible at the point of sale. However, a signal to customers is the price of the product; they attribute a higher price as signaling higher quality. A respondent gave direct and brief quote:

"For spending such amount of money, it has to work."

This was a very common sentiment in the open-ended discussion. Respondents felt the high price of PV systems was an indication that they would work properly. Some felt more confident it would work because they have seen off-grid solar electricity used by their families and by the state government to power street lights, and the fact it was powered by the sun. In addition, some people reported seeing their neighbors or friends using the product. A majority of respondents think off-grid solar electricity would serve their electricity needs and save them money as compared to power from the electrical grid and generators. The same sentiment applied to solar chargers.

On the other hand, some people still felt less confident because of lack of trust with the sellers of the technology. People expressed concerns with durability based on their negative experiences with solar products that are similar in size with solar chargers. A respondent said:

> "Dealing with electronics is a game of chance. It may or may not work."

Another respondent said:

> "I've used a few of these chargers and the problem with them is the short lifespan. My confidence is halfway."

In regard to generators and fuel cost, we asked households about the state of electricity in their households. They experienced long periods of blackouts and expressed frustrations with the electricity situation. To address electricity challenges, households turn to petrol-powered generators for electricity. Slightly over 50% of the total sample from both surveys reported they own a generator and spent an average of $5.57 weekly on petrol. Households that did not own generators depended on their neighbors and businesses in the area for electricity.

To understand the means by which households access electricity, we used cell phone charging as a proxy for electricity use. It provides an understanding of how they adapt to the inconsistent power supply. A majority of households reported they charged their cell phones at home; however, due to the power inconsistencies they use petrol-powered generators to charge their phones. Households that cannot afford generators or petrol and want to charge their phones for free, go to their neighbor's house to charge their phones, or they charge their phones at work, school, and local businesses like barber shops, hotels and gas stations. Sometimes if neighbors can't provide electricity, they go to businesses that provide electricity at a price. Only 8.4% of the total sample reported they pay others to charge their cell phones; the average cost they spent on charging was $0.27 per charge. Such people only charge their phones twice a week and it is off after the battery runs out or the phone is turned off much of the time in order to avoid having to charge it every day.

We asked households a series of questions about different ways they would consider owning a PV system. We understood the price of PV systems might be too high for households but we wanted to investigate if they were willing to consider alternatives to owning a PV system alone for personal use. The first option offered to them was to own PV systems as a group. This was asked to see if households were willing to share the cost and benefits of PV systems. The second option offered was to own PV systems individually. The next option offered was for households to buy PV systems and use them to sell electricity, thereby becoming an energy supplier. This was asked to see if households would consider PV systems as a way to make income.

The majority of households stated they prefer to own individually, so that they have the flexibility to buy the size they need to meet their own needs. Also, with owning individually, some people expressed that they could help their community by granting access to their homes to use electricity. According to our data, 12.9% stated they were willing to own PV systems as part of a group. Although it would reduce the cost of owning a PV system, the vast majority of people anticipated it would lead to challenges because they don't think people would use their fair amount and the arrangement would be abused. About 17.7% stated they were willing to own PV systems to sell electricity. This would create an opportunity to pay back money if they borrowed it to buy a PV system, or it could serve as an additional income source while also meeting their electricity needs. However, most of the households expressed concerns with people not paying for the services and did not want to deal with debtors. They also expressed concern about the technical complications associated with the transmission of electricity.

2.4.2 Choice experiment results

The results of the Random Parameter Logit (RPL) model for PV systems are reported in Table 4. Looking at the RPL results, all the coefficients are significant except for hours. The price attribute is negative as expected, meaning that the higher the price of PV systems, the lower the propensity of respondents to choose such PV systems. The negative sign associated with watts (amount of power) for PV implies that people would prefer to purchase a smaller system than a larger one. It is consistent with what households expressed in the survey that people might want less to power until they can trust the technology. In addition, in Chapter 1 we found that most households do not have many appliances or need much electricity.

The negative sign associated with savings which is related to the amount of money households spend on fuel monthly, implies that people would prefer a system that would save them less fuel. The result is not consistent with our expectation, and our data was not able to explain the reason for the finding. A hypothesis can be that petrol is heavily subsidized in Nigeria. With respect to the country in which PV systems are manufactured, people prefer if the PV systems are manufactured in the United States as compared to China. For the respondents that opted out the coefficient was negative, and significant, indicating they get disutility from choosing PV systems. It means they are happier with their current situation and it is more preferred, so they are not willing to purchase PV systems.

The results from the estimation in the willingness to pay (WTP) model capture households' valuation of PV system attributes. Households are willing to pay $173.58[1] more for PV systems made in the United States compared with China. This represents that households are willing to pay more for products they trust more.

Table 2.4: Random parameter model Results for PV systems

	Preference space		WTP space	
	Coefficient	Std. error	WTP	Std. error
Price	-0.00081***	0.00026		
Hours	-0.00435	0.00909		
Watts	-0.00427***	0.00034	-5.17909	3.12118
Country	0.14188**	0.05534	173.58276	148.91802
Savings	-0.00480**	0.00199	-5.89537	0.240364
Opt-out	-6.39907***	0.34526		
Model fit statistics				
N	1799			
Log-likelihood	-1238.24524			
AIC	2496.5			

Note: ***, **, * represent significance at the 1%, 5%, and 10% levels. Multinomial logit model estimated using NLOGIT 5.0 based on 1000 Halton draws used for simulated Maximum likelihood

The results from the solar charger choice model are reported in Table 5. Looking at the RPL results, the only coefficients that are significant are price and country. The price attribute is positive, meaning that the higher the price of solar chargers, the higher the propensity that people want to choose them. We acknowledge that this is not the norm in choice experiments, but it is consistent with the idea that people associate price with quality and that they don't want to buy something that will break. It will be discussed further in the discussion section below.

With respect to the country in which solar chargers are manufactured, people prefer if the solar chargers are manufactured in the United States as compared to China.

[1] For other attributes like Watts and Savings households were willing to pay $5.18 less and $5.89 less respectively. It was difficult to explain the results.

For the respondents that opted-out, the coefficient of opt-out was negative and significant, indicating they get disutility from choosing solar chargers. It means they are happier with their current situation and it is more preferred, so they are not willing to purchase a solar charger.

Table 2.5: Random Parameter Model Results for Solar Chargers

	Preference space	
	Coefficient	Std. error
Price[2]	0.01942*	0.01069
Hours	0.04934	0.03828
Watts	0.01216	0.00772
Country	0.53076***	0.15501
Opt-out	-5.00189***	0.24140
Model fit statistics		
N	1871	
Log-likelihood	-1180.59	
AIC	2377.2	

Note: ***, **, * represent significance at the 1%, 5%, and 10% levels. Multinomial logit model estimated using NLOGIT 5.0 based on 1000 Halton draws used for simulated Maximum likelihood

2.5 Discussion

There is a shortage of electricity in Nigeria, where households are heavily dependent on generators and other means to meet their electricity demand. From the survey, close to 50% of the households sampled own generators. However, there is still demand for more electricity, which off-grid solar electricity can help to meet. Nevertheless, there are challenges that households face. The obvious challenge is the affordability of off-grid solar electricity given their income. In the sample about 40% of the households reported income of less than $14 per week. This demonstrates how challenging it will be for households to purchase off-grid solar electricity.

First, in the survey we explored trust and found that households were slightly more trusting of PV systems than solar chargers. Overall, they expressed concerns with the quality of the products in the market. Since there are no warranties on products, households always felt cheated and cynical based on their bad experiences buying products that don't work well or don't last. However, since their electricity situation is so dire most respondents indicated that they are willing to try off-grid solar

[2] Willingness to pay coefficient was omitted since the price coefficient was positive

electricity. In addition, prices for PV systems might be too high for many households given their low-income levels. The survey explored if they would be willing to share the cost as a group in the community, but that option was the least popular followed by owning to sell electricity. Most households preferred to own individually because they could not anticipate the demand of other households.

The choice experiment (CE) was designed with households' income levels taken into consideration, so that we could study the influence on people's willingness to pay for solar technology. We focused on two markets for off-grid solar electricity: PV systems and solar chargers. Comparison between both markets are: PV systems cost at least 10 times the price of solar chargers and also provide far more power. Given their income levels we wanted to understand tradeoffs households are willing to make for each technology separately. The results showed that trust is what is really important to the households as indicated by the coefficient for country. PV systems are a relatively unknown technology, and people have had bad experiences with technology in the past and need something they can trust. The households are willing to pay 30 to 70 percent more for a PV system made in the United States compared to one from China; as mentioned, this is our proxy for trust since people have greater trust in products from the United States than China.

From the results it seems like the amount of power a system generates (watts) is not a particularly important attribute. An explanation is that households are more concerned with products that work than the amount of power they generate. In addition, they are more concerned with stable electricity than the amount they get, and this is what off-grid solar electricity offers. People don't necessarily need a lot of electricity but they want to be able to use the appliances they have.

In the CE results for solar chargers, trust was also the most important variable as households in our sample preferred chargers made in the United States to those made in China. Households associated higher priced solar chargers with quality and preferred chargers they could trust more. This result is critical because the prices of solar chargers are between $28-$54 and a majority of the households earn less than $42 a month, so it is affordable for their income range.

One very interesting result for solar chargers is the positive coefficient for price. People commented that they previously had had many bad experiences with small electronics, and they said that they expected that a more expensive product will likely be of higher quality. In addition, households limited access to sources that can provide them with information about potential products, due to high cost of data to browse the internet, and they don't have enough electricity on keep up with the news from television and radio. Therefore, the cost for them to access information is high, so they attribute higher prices with quality for new products (Bagwell & Riordan, 1991; Zeithaml, 1988). Data suggested that households treated solar chargers differently than PV systems. They considered solar chargers like other small electronics as cheap and non-durable.

2.6 Conclusion

While off-grid electricity has numerous advantages over the current grid and petrol-powered generators, it still faces significant barriers to adoption by households. In some instances, it may be more appealing to households with higher income and energy needs, but the lack of trust in the product is a deterrent. They also preferred to own PV systems individually rather than as a group or as an energy entrepreneur.

These findings have implications for energy companies that make off-grid electricity technology; it can contribute to how they design their products, pricing policies and market segmentation of households in Nigeria. The households are conscious of the quality of the product. Energy companies can increase their revenue by providing warranties for customers and more information about the product. This will, at the same time provide more access to off-grid electricity for households.

The findings can also contribute to the rural electrification policy for Nigeria. The policy seeks to increase electrification of rural households and also add renewable sources to the energy mix. The Standards Organization of Nigeria (SON), which is responsible for quality control, certification and circulation of information around solar systems can use the findings to ensure quality products are introduced to market. This can reduce the number of defective products on the market while increasing the trust of households in this technology.

REFERENCES

REFERENCES

Adeoti, O., Oyewole, B. A., & Adegboyega, T. D. (2001). Solar photovoltaic-based home electrification system for rural development in Nigeria: domestic load assessment. *Renewable Energy*, *24*(1), 155–161. https://doi.org/10.1016/S0960-1481(00)00188-9

Adurodija, F. ., Asia, I. ., & Chendo, M. A. . (1998). The market potential of photovoltaic systems in nigeria. *Solar Energy*, *64*(4–6), 133–139. https://doi.org/10.1016/S0038-092X(98)00095-4

Aliyu, A. S., Ramli, A. T., & Saleh, M. A. (2013). Nigeria electricity crisis: Power generation capacity expansion and environmental ramifications. *Energy*, *61*, 354–367. https://doi.org/10.1016/J.ENERGY.2013.09.011

Bagwell, K., & Riordan, M. H. (1991). High and Declining Prices Signal Product Quality. *The American Economic Review*, *81*(1), 224–239. Retrieved from http://www.jstor.org/stable/2006797

Bennett, J., & Birol, E. (2010). *Choice Experiments in Developing Countries*. Edward Elgar Publishing.

Blood, A., Zatorre, R., Shiv, B., & Rangel, A. (2008). Intensely pleasurable responses to music correlate with activity in brain regions implicated in reward and emotion. *PNAS*, *98*(20), 11818–11823. https://doi.org/10.1073/pnas.191355898

Chan, Y.-S., & Leland, H. (1982). Prices and Qualities in Markets with Costly Information. *The Review of Economic Studies*, *49*(4), 499. https://doi.org/10.2307/2297283

Hensher, D. A., Rose, J. M., & Greene, W. H. (2015). *Applied Choice Analysis*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781316136232

Ikeme, J., & Ebohon, O. J. (2005). Nigeria's electric power sector reform: what should form the key objectives? *Energy Policy*, *33*(9), 1213–1221. https://doi.org/10.1016/J.ENPOL.2003.11.018

Kabir, E., Kumar, P., Kumar, S., Adelodun, A. A., & Kim, K.-H. (2018). Solar energy: Potential and future prospects. *Renewable and Sustainable Energy Reviews*, *82*, 894–900. https://doi.org/10.1016/J.RSER.2017.09.094

Karakaya, E., & Sriwannawit, P. (2015). Barriers to the adoption of photovoltaic systems: The state of the art. *Renewable and Sustainable Energy Reviews*, *49*, 60–66. https://doi.org/10.1016/j.rser.2015.04.058

Lancaster, K. (1966). A New Approach to Consumer Theory. *Chicago Journals*, *74*(2), 132–157.

Lancsar, E., & Louviere, J. (2008). Conducting Discrete Choice Experiments to Inform Healthcare Decision Making. *PharmacoEconomics*, *26*(8), 661–677. https://doi.org/10.2165/00019053-200826080-00004

Nigerian Electricity Regulatory Commission. (2018). Electricity: Generation, Transmission, Distribution and Market Financial. Retrieved March 6, 2018, from http://www.nercng.org

Nigerian Electricity Regulatory Commission (NERC). (2017). NERC Third Quarter Report 2017. Retrieved July 27, 2018, from http://www.nercng.org/index.php/component/remository/NERC-Reports/NERC-Third-Quarter-Report-2017/?Itemid=591

O. Oji, J., Idusuyi, N., O. Aliu, T., O. Petinrin, M., A. Odejobi, O., & R. Adetunji, A. (2012). Utilization of Solar Energy for Power Generation in Nigeria. *International Journal of Energy Engineering*, *2*(2), 54–59. https://doi.org/10.5923/j.ijee.20120202.07

Ogunleye, I. (2011). Constraints to the use of solar photovoltaic as a sustainable power source in Nigeria. *American Journal of Scientific and Industrial Research*, *2*(1), 11–16. https://doi.org/10.5251/ajsir.2011.2.1.11.16

Oladeji, A. S., & Sule, B. F. (2016). Rural Households Energy Needs and Consumption Pattern : A Case of Beri Village , Kwara State , Nigeria, *21*(1), 2–7.

Ortega, D. L., Waldman, K. B., Richardson, R. B., Clay, D. C., & Snapp, S. (2016). Sustainable Intensification and Farmer Preferences for Crop System Attributes: Evidence from Malawi's Central and Southern Regions. *World Development*, *87*, 139–151. https://doi.org/10.1016/j.worlddev.2016.06.007

Oyedepo, S. O. (2012). On energy for sustainable development in Nigeria. *Renewable and Sustainable Energy Reviews*, *16*(5), 2583–2598. https://doi.org/10.1016/j.rser.2012.02.010

Sambo, A. (2008). Matching electricity supply with demand in Nigeria. *International Association for Energy Economics*, (4), 32–36. Retrieved from http://expertscolumn.com/content/matching-electricity-supply-demand-nigeria

Sarzynski, A., Larrieu, J., & Shrimali, G. (2012). The impact of state financial incentives on market deployment of solar technology. *Energy Policy*, *46*, 550–557. https://doi.org/10.1016/j.enpol.2012.04.032

Scarpa, R., & Willis, K. (2010). Willingness-to-pay for renewable energy: Primary and discretionary choice of British households' for micro-generation technologies. *Energy Economics*, *32*(1), 129–136. https://doi.org/10.1016/J.ENECO.2009.06.004

Smith, E. M., & Broome, C. (1966). Experimental Determination of the Effect of Price and Market-Standing Information on Consumers' Brand Preferences. Chicago: Proceedings of the 1996 Academy of Marketing Science (AMS) Annual Conference.

Waldman, K. B., Ortega, D. L., Richardson, R. B., & Snapp, S. S. (2017). Estimating demand for perennial pigeon pea in Malawi using choice experiments. *Ecological Economics*, *131*, 222–230. https://doi.org/10.1016/j.ecolecon.2016.09.006

Zeithaml, V. A. (1988). Consumer Perceptions of Price, Quality, and Value: A Means-End Model and Synthesis of Evidence. *Journal of Marketing*, *52*(3), 2. https://doi.org/10.2307/1251446

Zeithaml, V. A. (1988). Consumer Perceptions of Price, Quality, and Value: A Means-End Model and Synthesis of Evidence. *Journal of Marketing*, *52*(3), 2. https://doi.org/10.2307/12514

CHAPTER 3: SYSTEM DYNAMICS SIMULATION OF OFF-GRID SOLAR ELECTRICITY ADOPTION IN NIGERIA

3.1 Introduction

There is an energy deficit in African countries most especially in the rural areas, with demand outstripping supply. Currently, 90 million people lack access to the electrical grid in Nigeria and addressing the problem has become increasingly challenging, as the population increases, and the central electrical grid deteriorates (International Energy Agency, 2017; Rural Electrification Agency, 2018). There are challenges with the generation and transmission of electricity from the grid. For instance the grid only generates at close to 50% capacity (Nigerian Electricity Regulatory Commission, 2018).

The Nigerian Government's target is to achieve up to 75% access to electricity by 2020 by connecting an average of 1.5 million households annually through grid extension as well as non-grid solutions, using renewable energy like solar and wind (Rural Electrification Agency, 2018). The government has made efforts to understand and tackle the electricity crisis, but it is facing difficult challenges. Studies conducted on the electricity situation indicate the absence of effective institutional and legislative mechanisms, corruption in leadership, and inadequate human resources (Aliyu et al., 2013). A potential solution is the use of solar technology to generate off-grid solar electricity from Photo-voltaic systems (PV systems), and solar chargers that households can individually purchase. These types of technology are said to be flexible, cost effective and can meet the basic demands of rural households (Nouni et al., 2008). They can also provide enough power to charge items like cell phones and rechargeable lamps. Despite the advantages of off-grid solar electricity, the adoption rate is very low in Nigeria (International Energy Agency, 2017). In Nigeria, solar power is only about 0.1 % of the energy supply (Sambo, 2008)

3.2 Objectives and Research questions

The challenge is to understand how, if, and when a technology will be adopted by end users and to understand the mechanisms behind off-grid solar electricity adoption in Nigeria. In this research I seek to capture the complex interactions and dynamic feedbacks between household preferences, socio-economic systems and household perception of off-grid solar electricity in Nigerian households.

A system dynamics model is applied to integrate knowledge of the feedback processes and long-term dynamics of off-grid solar electricity adoption in Nigerian households. System dynamics is based on servo-mechanism and feedback control theory (Kotir, Smith, Brown, Marshall, & Johnstone, 2016; Sahin, Stewart, & Porter, 2015). The method uses time delays, non-linearity, and feedback loops to understand the behavior of complex system. In addition, it provides a way to demonstrate interactions within a system (Kotir et al., 2016). It is an insightful tool used that can be used to understand adoption behavior.

System dynamics (SD) has been used to model technology adoption, for example to understand technology adoption effects on agribusiness management (Fisher, Norvell, Sonka, & Nelson, 2000). Another study used SD to assess the impact of technology on retail operations like inventory, turnover, and worker efficiency (De Marco, Cagliano, Nervo, & Rafele, 2012). SD has also been used to model the energy efficient lighting diffusion process in households (Tilman, Balzer, Hill, & Befort, 2011).

The overall research seeks to answer the question: what are the drivers of adoption for off-grid solar electricity over time? The objectives are the following:

a. Assess the impact of lowering the price of off-grid solar electricity on adoption behavior by rural households over time.
b. Understand the effect of consumer preference and trust on adoption of off-grid solar electricity.

c. Investigate the effect of product life span on dis-adoption of off-grid solar electricity.
d. Finally, provide an understanding of how market access affects adoption of off-grid solar electricity.

3.3 Study context and scope

The study was conducted in southwest Nigeria, in Ogun state in a community called Ayetoro. The state community shares a border with the country Benin. The electricity the town receives varies from approximately one hour to three hours per day, and the supply of electricity is intermittent (Chapter 1). The major use for electricity in the town is for lighting, cell-phone charging and entertainment. To meet the shortfall in electricity supply, some households use petrol-powered generators to meet their needs. However, not every household can afford generators and the recurring cost of petrol. In the household energy survey conducted in the community, only about 50 percent of households reported they owned generators (Chapter 1).

The Nigerian electricity regulatory commission (NERC) indicated the challenges associated with supply have to do with electricity generation and transmission. The plants are outdated, poorly maintained and are not functioning at peak levels (Nigerian Electricity Regulatory Commission (NERC), 2017). Furthermore, there are challenges in getting gas supply to the power plant to generate electricity. After electricity is generated, close to 50 percent is lost during transmission to households, due to poor electrical infrastructure. Of the households that receive electricity, over 60 percent are located in urban areas and the rest in rural areas (International Energy Agency, 2017).

3.4 Methodology

3.4.1 Theoretical framework for the design of the model

The diffusion process of a new technology through a population is driven by information exchange between individuals. It can involve mass media or word of mouth from individuals (Rogers, 1976). Initially, households and communities learn of the off-grid solar electricity, form an attitude about it, evaluate the relative advantages, decide whether to adopt it or not, and then finally evaluate the performance of the PV systems and solar chargers. Furthermore, diffusion is a dynamic process that goes from adopting a technology to dis-adopting and vice versa (Rogers, 2010). For example, households can purchase or acquire a technology, then later stop using the technology and then after a period can reacquire the technology or never use the technology again. The Bass diffusion model captures the dynamic process explained by Rogers (2003). The Bass diffusion model was used as a framework for this modeling work along with data collected in the field (refer to chapter 1) to develop a conceptual model (Figure 3.1 and Figure 3.2) to understand the drivers of adoption over time for off-grid solar electricity in Nigeria (Bass, 2004). Figure 3.1 is the conceptual model for PV system adoption (refer to chapter 1 for more information on PV systems). The model depicts how adoption is affected by market access, trust, product quality, household preference, market share for off-grid electricity between petrol-powered generators and PV systems, and electricity bill. Figure 3.2 is a conceptual model for solar chargers (refer to chapter 1 for more information on solar chargers). The model depicts how adoption is also affected by the same factors as PV systems with the exception of market share because solar chargers are in a different consumer market than PV systems and petrol-powered generators.

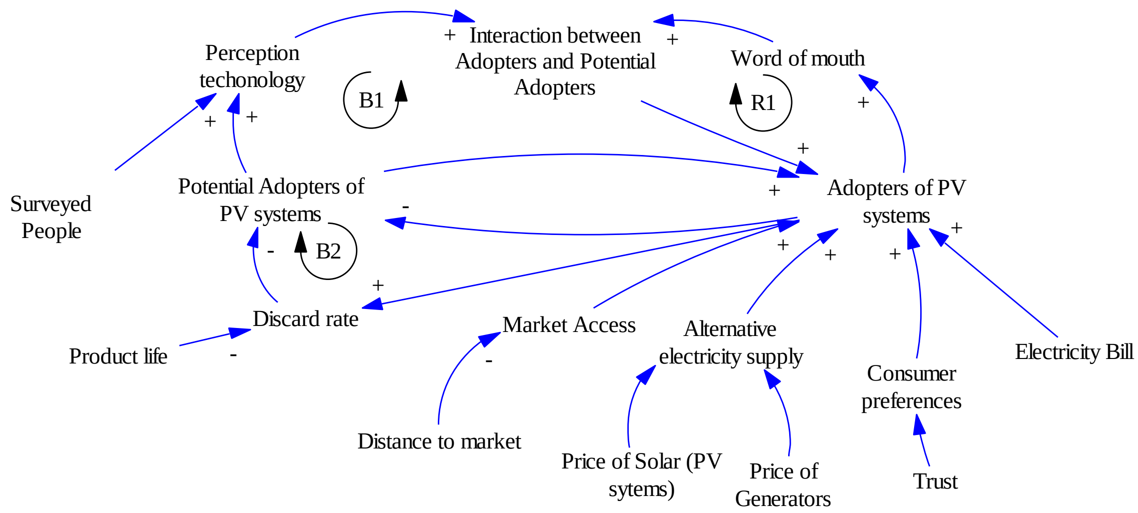

Figure 3.1: Conceptual model of household preferences, socio-economic systems and household's perception of PV systems. R depicts a reinforcing loop and B depicts a balancing loop. The positive sign indicates a direct relationship between variables, while the negative sign indicates an inverse relationship

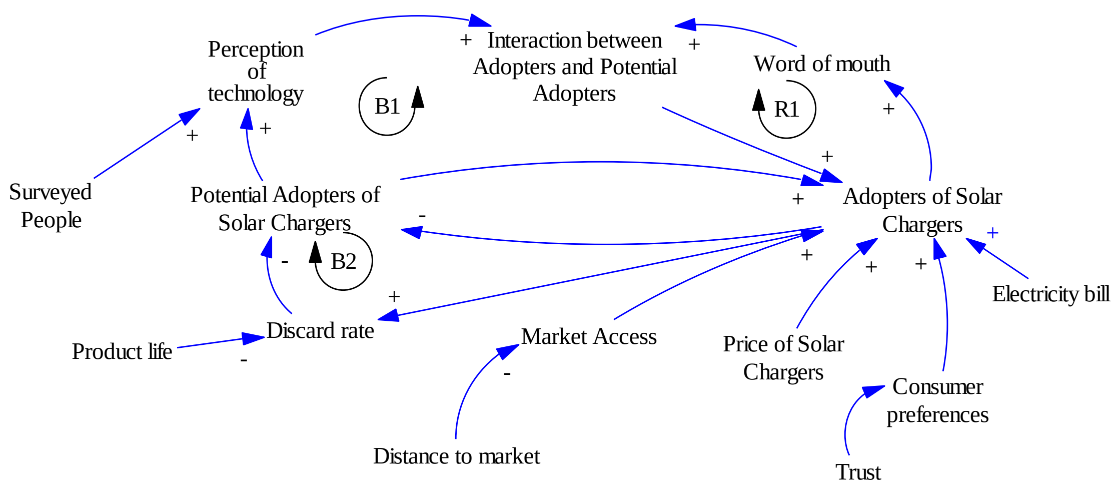

Figure 3.2: Conceptual model of household preferences, socio-economic systems and household's perception of off-grid solar chargers. R depicts a reinforcing loop and B depicts a balancing loop. The positive sign indicates a direct relationship between variables, while the negative sign indicates an inverse relationship

The conceptual model also known as the causal loop diagram (CLD) is used to help understand the dynamic behavior of the system (Ford, 2010). The diagram is beneficial in representing the qualitative relationship amongst variables (Sterman, 2000). The CLD for household preferences, socio-economic systems and perception of off-grid solar electricity is depicted in Figure 3.1 and Figure 3.2.

The positive sign in Figure 3.1 and Figure 3.2 indicates a direct relationship between variables, while the negative sign indicates an inverse relationship; dual causal relationships lead to feedback loops (Sterman, 2000). Feedback loops demonstrate a cause and effect relationship in a closed system (Ford, 2010). The feedback loops can either be a (positive) reinforcing loop (R) or (negative) balancing loop (B). The positive loop pushes change in the system that can result in accelerated growth or decline, while the balancing loop can counteract or oppose variation in the system (Kotir et al., 2016).

The loops in the model show the dynamic process of diffusion. As shown in Figure 3.1 and Figure 3.2 there are three major loops in the model. The first loop is a reinforcing loop (R1) between adopters of off-grid solar electricity, word of mouth, interaction between potential adopters and adopters. Households that own off-grid solar electricity will talk more about the technology, which will increase interactions with potential adopters and increase the number of adoptions. So, the feedback loop acts as a reinforcing loop.

The second loop is a balancing loop (B1) between potential adopters of off-grid solar electricity, adopters of off-grid solar electricity, perception of technology and interaction between adopters and potential adopters. Potential adopters have a perception about the technology that leads to interactions with adopters, hence an increase in adoption and a decrease in potential adopters. So, the feedback loop acts as a balancing loop.

The third loop is a balancing loop (B2) between potential adopters of off-grid solar electricity, discard rate, and adopters. As more people adopt the technology, it correlates with a higher number of discards of the technology and leads to lower potential adopters. So, the feedback loop acts as a balancing loop. Overall, Figure 3.1 consists of 16 systems variables, which are connected by 19 links and Figure 3.2 consists of 14 systems variables, which are connected by 17 links.

3.4.2 Model setting

The causal loop diagram illustrates the relationships between key variables in the system and it provides a basis for the SD model. The off-grid solar electricity adoption SD model consists of interaction between potential adopters and adopters. The SD model consists of stocks and flows, the stocks are levels or accumulation and flows represent the rates between the stocks. The stocks in the model are potential adopting households, and adopters of off-grid solar electricity. The flows of the model are adoption, and discard of off-grid solar electricity. The year 2038 was picked as for the model run time, because it represents the long-term perspective of households' adoption behavior.

The models were developed using information from the household energy survey, and inputs from households in the community (Chapter 1). The participants were selected at random and the sample included households from different income levels, home owners, renters, university students, professionals and farmers. The selection process was also designed to include households that were connected to the grid and off grid, and households that used petrol powered generators as an alternative electricity source to grid. The models were refined and structurally validated. The models were constructed using Vensim software (http://vensim.com/vensim-software/). The SD models have a time step of 0.25 years, which indicates the scale at which households would decide to adopt PV systems or solar chargers. The values of stocks and flows was simulated every timestep.

3.4.3 Model descriptions and parameterization

The model estimates the number of adopters is influenced by the adoption and discard rates, as well as word of mouth. Consequently, the total number of adopters was calculated as the number of adopters minus the number of people that discard the technology. In addition, other factors that affect adoption behavior include price, product life, perception of technology, word of mouth, trust, distance to market, electricity cost per unit, and alternatives for electricity.

Price has been identified as the most significant socio-economic factors that influences adoption of off-grid solar electricity (Chapter 2). In this study we split the off-grid solar electricity into two markets: PV systems and solar chargers (Figure 3.3 and Figure 3.4), to understand adoption behavior at different consumer markets. The Solar charger model (Figure 3.4) addressed a different market segment for off-grid solar; the price parameter was based on the market prices and online prices (Chapter 2). The highest price of solar charger was $14.16 and lowest price was $5.67, while the PV systems (Figure 3.3) had prices between $250 to $600 (Chapter 2). From the price effect in the model, we assume that prices for solar technology will reduce overtime (Candelise, Winskel, & Gross, 2013).

From the survey (Chapter 2), households observed and reported that similar technology like solar chargers, have a product life of less than 6 months. They also reported PV systems also have a short product life and are unreliable. We assume the product life affects the perception of the technology and can drive the mouth of mouth positively or negatively. We also assume that technology will improve over time, and we capture this effect in the model with improvement in product life (Candelise et al., 2013). We expect that adoption will increase as product life increases.

Another factor that affects adoption behavior is trust in the technology. From the survey (Chapter 2) households reported to have 71% trust in off-grid solar electricity. We assume consumers prefer technology they can trust (Chapter 2). Adoption behavior is also negatively influenced by the extent to which households must travel to buy the technology; in the model we classify it as market access (Chapter 1). Respondent households have to travel about 120 miles to a major market in Lagos, Nigeria to buy off-grid solar electricity (Chapter 1).

Electricity availability from the grid is determined by several factors, including the amount generated and transmitted from the grid, infrastructure conditions and the bill households pay for services. Households have expressed frustration with inconsistent supply along with electricity bills (Chapter 1). Because of the challenges with electricity from the grid, electricity cost per unit will continue to increase over time; we estimate an annual price increase of 5% (Chidebell-Emordi, 2015; Nigerian Electricity Regulatory Commission (NERC), 2017; Unachukwu, 2010).

Due to inconsistent supply of electricity, 60% households reported they own generators (Chapter 1). Petrol-powered generators are considered alternatives for electricity in the PV system model. They are comparable to PV systems because of their capacity, and dominate the Nigerian market (International Energy Agency, 2017). With regards to initial cost, petrol-powered generators cost $270 as compared to PV systems with the same capacity with a price of $570 (Chapter 2). We assume this can negatively affect adoption behavior of PV systems; however, we expect the prices of PV systems to continue to reduce over time (Candelise et al., 2013).

The data in the models are community, representative of conditions in Ogun State, Nigeria. The population variable in the model was based on the amount of people in the survey. The initial values used to parameterize the model were obtained from surveys conducted in Chapter 1 and Chapter 2. Additional information of key parameters in the models can be found in Table 3.2 in Appendix. All assumptions are based on respondents' suggestions and literature.

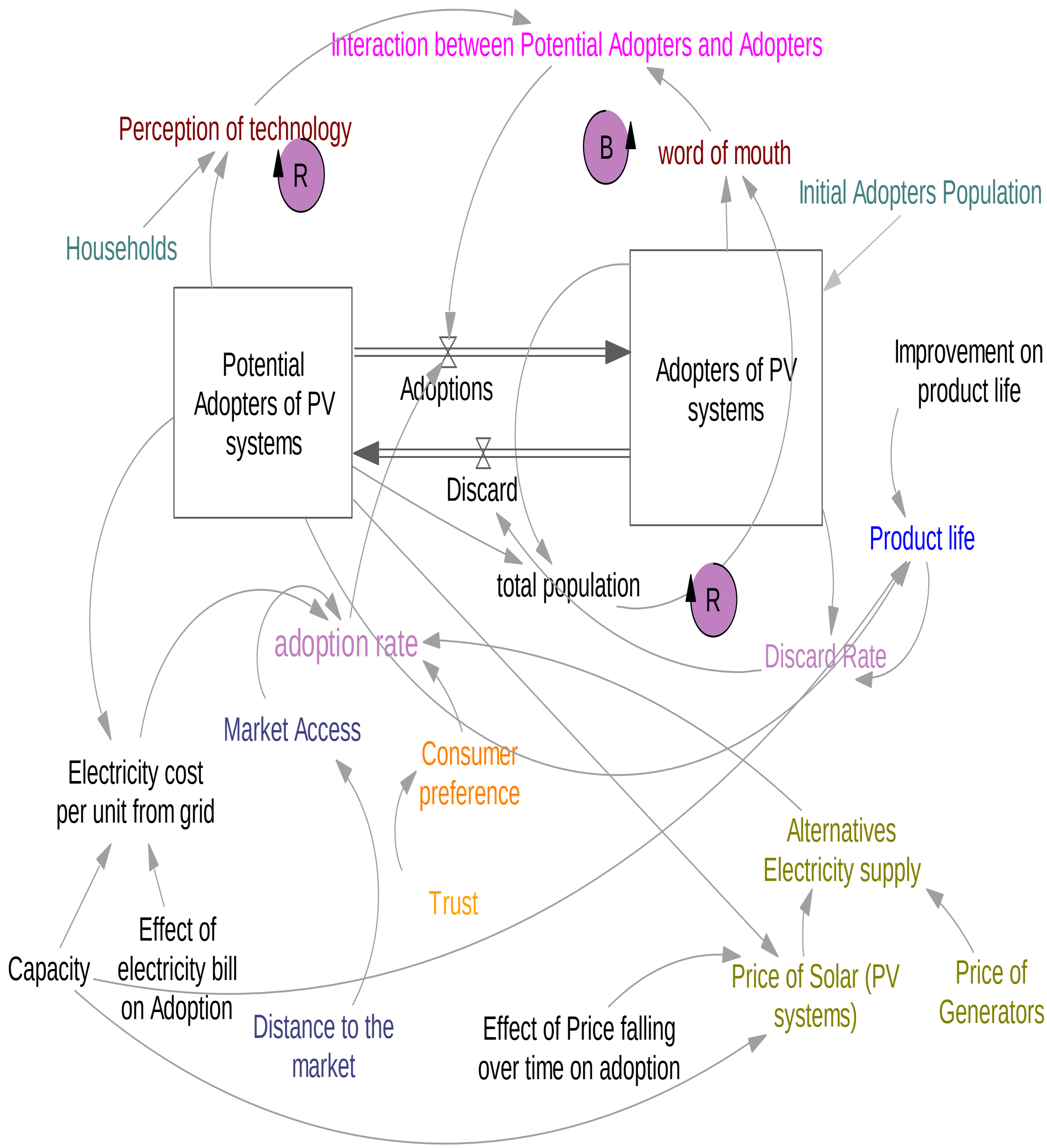

Figure 3.3: System Dynamics Model for PV systems between potential adopters and adopters

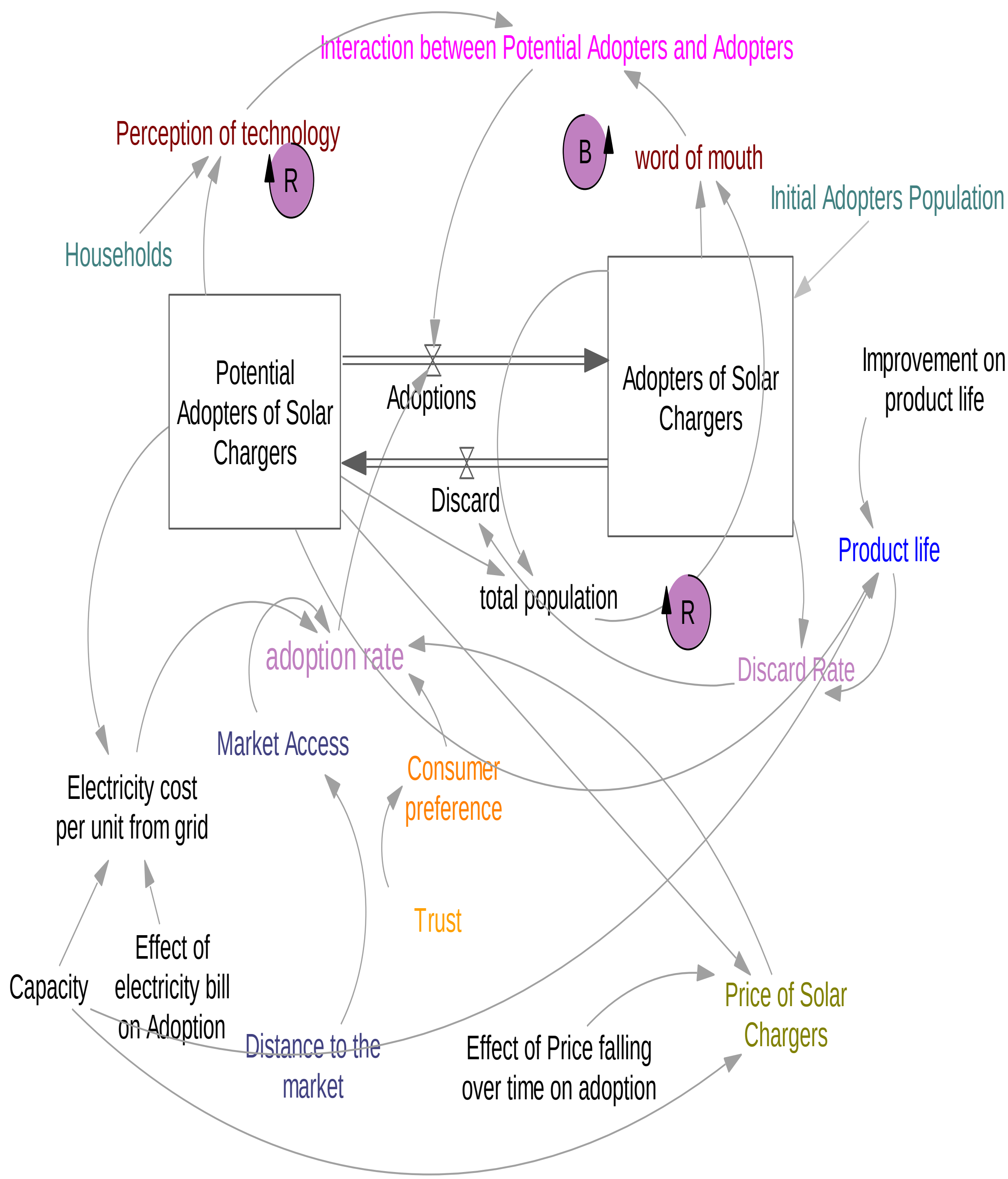

Figure 3.4: System Dynamics Model for Solar Chargers between potential adopters and adopters

3.4.4 Model Testing

The purpose of this model was to evaluate a two-stock system of both potential adopters and adopters of off-grid solar electricity. However, we don't have historical data on observed adoption behavior of off-grid solar electricity in Nigeria. To validate the model, we tested the model's parameters under extreme conditions to see if the model's response is credible (Ford, 2010). For instance, we subjected the distance to market to extreme values to see if the model will exhibit erroneous behavior. We also subjected other parameters like word of mouth and trust to extreme values.

3.4.5 Sensitivity Analysis

Sensitivity analysis was carried out to identify model parameters that had the most effect on adoption behavior of the model (Kotir, Smith, Brown, Marshall, & Johnstone, 2016). To perform sensitivity analysis several simulation runs were conducted. For each of the runs only the values of the selected parameters were changed by ±10% and others were held at their steady state levels. Similar studies have used this method to build confidence in system dynamics models (Guo et al., 2001; Kotir et al., 2016; Sahin et al., 2015). Sensitivity analysis therefore a useful tool for understanding adoption behavior as depicted in the model.

3.4.6 Scenarios Design

After sensitivity analysis was conducted, different scenarios were designed to assess adoption behavior. First, the base case scenario assumes current market conditions for off-grid solar electricity: Prices of PV systems will decrease over time, electricity bill of households will increase over time, quality of technology will improve over time, and socio-economic conditions within the Ayetoro community would remain the same without any policy or perception changes (Candelise et al., 2013;

Chidebell-Emordi, 2015; Unachukwu, 2010). Besides the base model, four additional scenarios were designed and simulated for both PV systems and solar chargers.

Scenario 1 (Price and government policy): simulates the effects on price of government policies. As stated in Nigeria's Rural Electrification Act, the government seeks to increase electricity access to communities (Rural Electrification Agency, 2018). The goal of the act is to increase electricity access and also increase the amount of renewable energy in the mix. One important strategy is for the government to provide subsidies or reduce import tax on the off-grid solar technology. Hence, we simulated a 30% price decrease in both PV systems and solar chargers. This scenario assumes the suppliers of off-grid solar technology will respond to the incentives of the government and supply more of the technology.

Scenario 2 (Trust): simulates the adoption of off-grid solar electricity with increased trust in the technology. Households in the survey (Chapter 2) reported negative experiences with solar technology. This affects their decreasing desire to buy the product and negative perception about the technology. We also understand consumers have preferences for technology they can trust (Chapter 1 and 2). Hence, scenario 2 simulates the response of households when they purchase technology they can trust. The scenario considered a 20% increase in trust through companies providing warranties for the technology.

Scenario 3 (Product life): households in the survey reported that they have observed short product life in solar technology. In addition, households that have not used the solar technology have observed the short product life of the technology. Hence, scenario 3 simulates the effect of product life on adoption. The scenario considered a 20% decrease in the effect on the consumer.

Scenario 4 (Market Access): explores the effect of distance to market from the Ayetoro community to Lagos where the technology is sold in markets. The distance is approximately 120 miles. As a result, the cost of transportation increases the overall costs for households to purchase solar electricity. Hence, scenario 4 considered a 50% decrease in distance to the market. The base case scenario will be compared to the results of the four additional scenarios to understand the different factors affecting adoption.

3.5 Results

3.5.1 Model testing

By subjecting both SD models to twice the distance to purchase off-grid solar electricity, our results show that adoption drops by 94.6% and 3.8% respectively for PV systems and Solar Chargers (Figure 3.5 and Figure 3.6). We also combined two parameters (trust and word of mouth) and subjected them to considerable low trust (20%) and word of mouth (10%), the results showed adoption of off-grid electricity approaches zero (Figure 3.5 and Figure 3.6). The extreme tests conducted on the model showed it was structurally sound and behavior of the model is plausible. The behavior is also consistent with what we learned about the community through surveys.

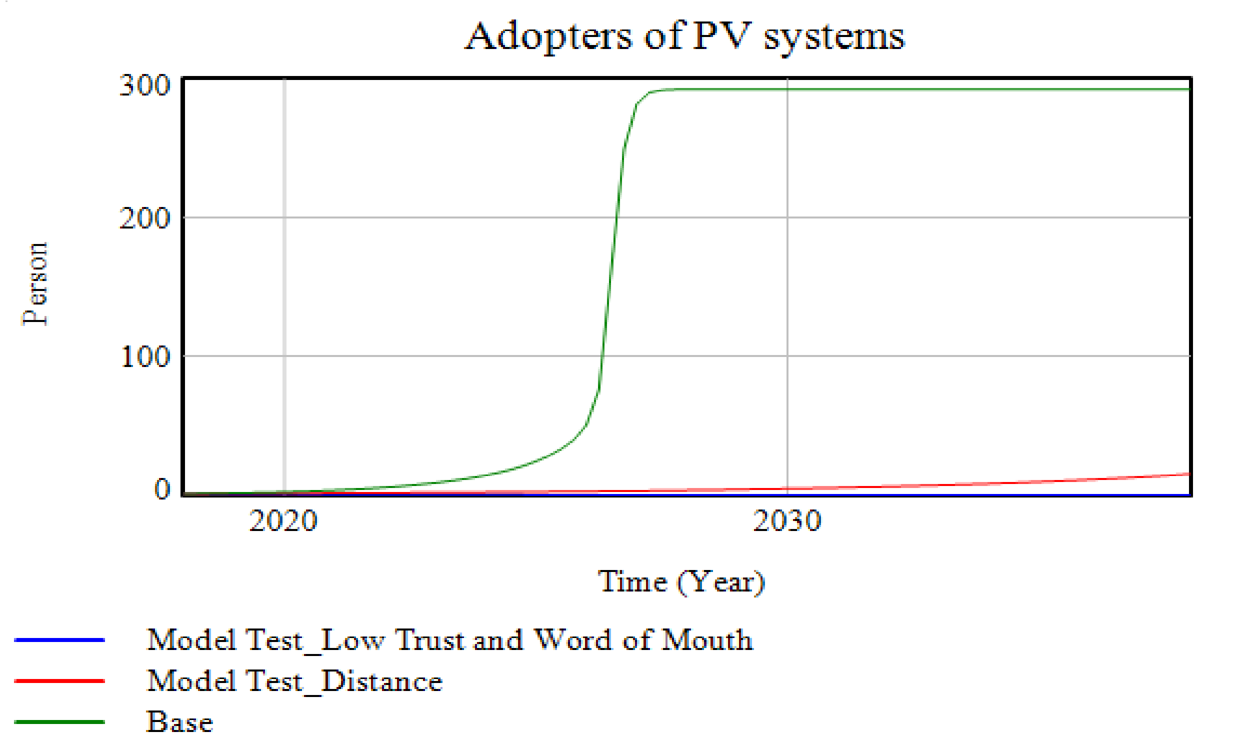

Figure 3.5: Model testing results for longer distance, low trust and word of mouth for PV systems

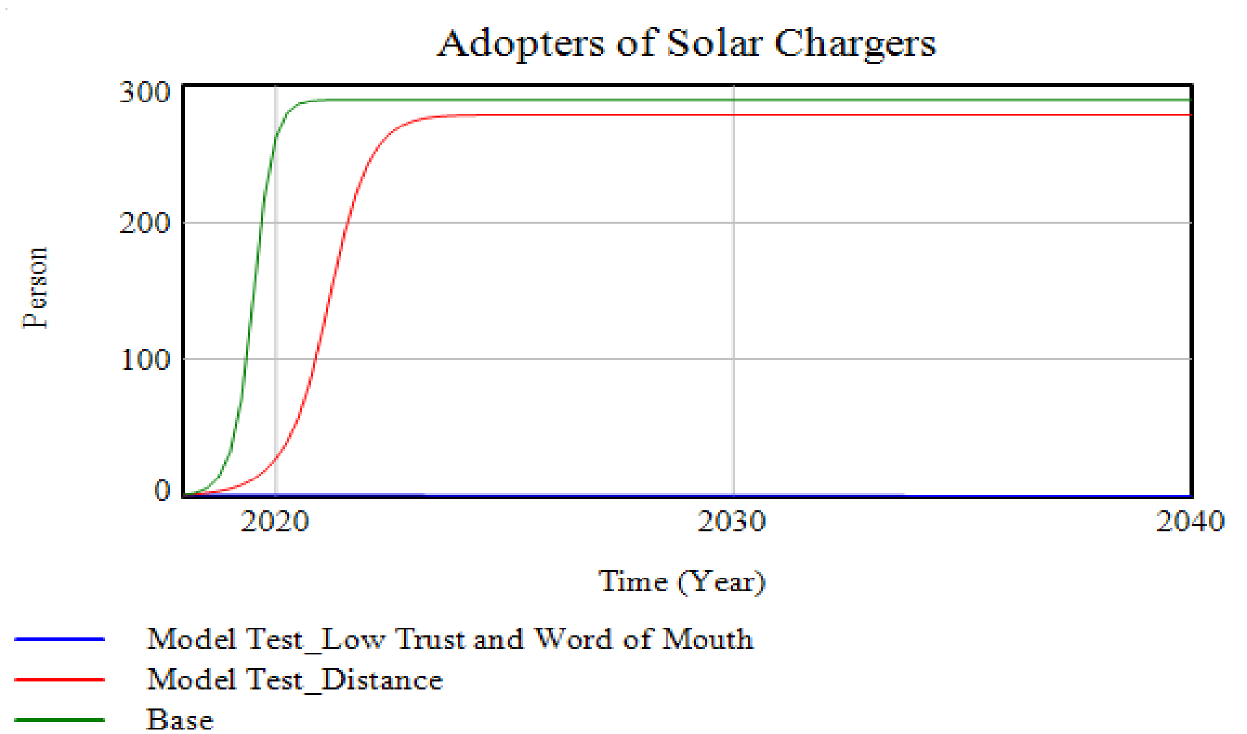

Figure 3.6: Model testing results for longer distance, low trust and word of mouth for Solar chargers

3.5.2 Sensitivity analysis: Photo-voltaic systems (PV systems)

Figures 3.7 and 3.8 illustrate the diffusion curves of the adopters of PV systems under baseline conditions, and with selected parameters changed by ±10%. In the baseline case, the adoption peaks around 10 years; there is a slow rise in the initial 5 years then a sharp rise after 8 years. Through the sensitivity analysis with the simulation of selected parameters at +10%, we find that the variables trust and word of mouth had the most effect on increasing adoption. Market access, product life and price of solar (PV systems) had the least impact on the speed at which all households adopt off-grid solar electricity. The simulation of selected parameters at -10% values indicate that trust and word of mouth had the most effect on decreasing adoption. Price of solar (PV), market access and product life have impact on increasing adoption dynamics. Changes to the selected parameters did not significantly change the model behavior over time.

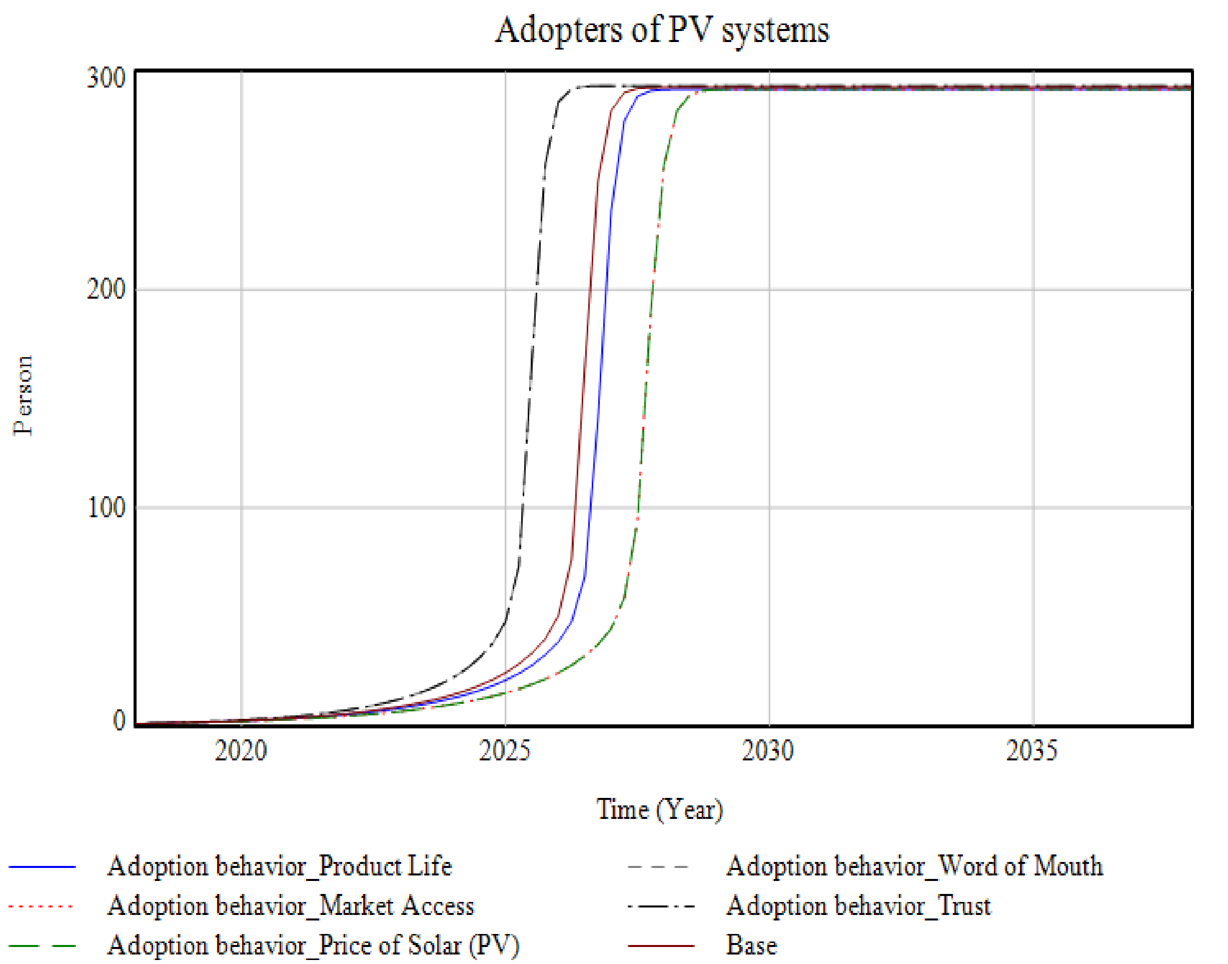

Figure 3.7: Differences in Adoption behavior with selected parameters changed one at a time by +10% The changed parameter is indicated after the underscore

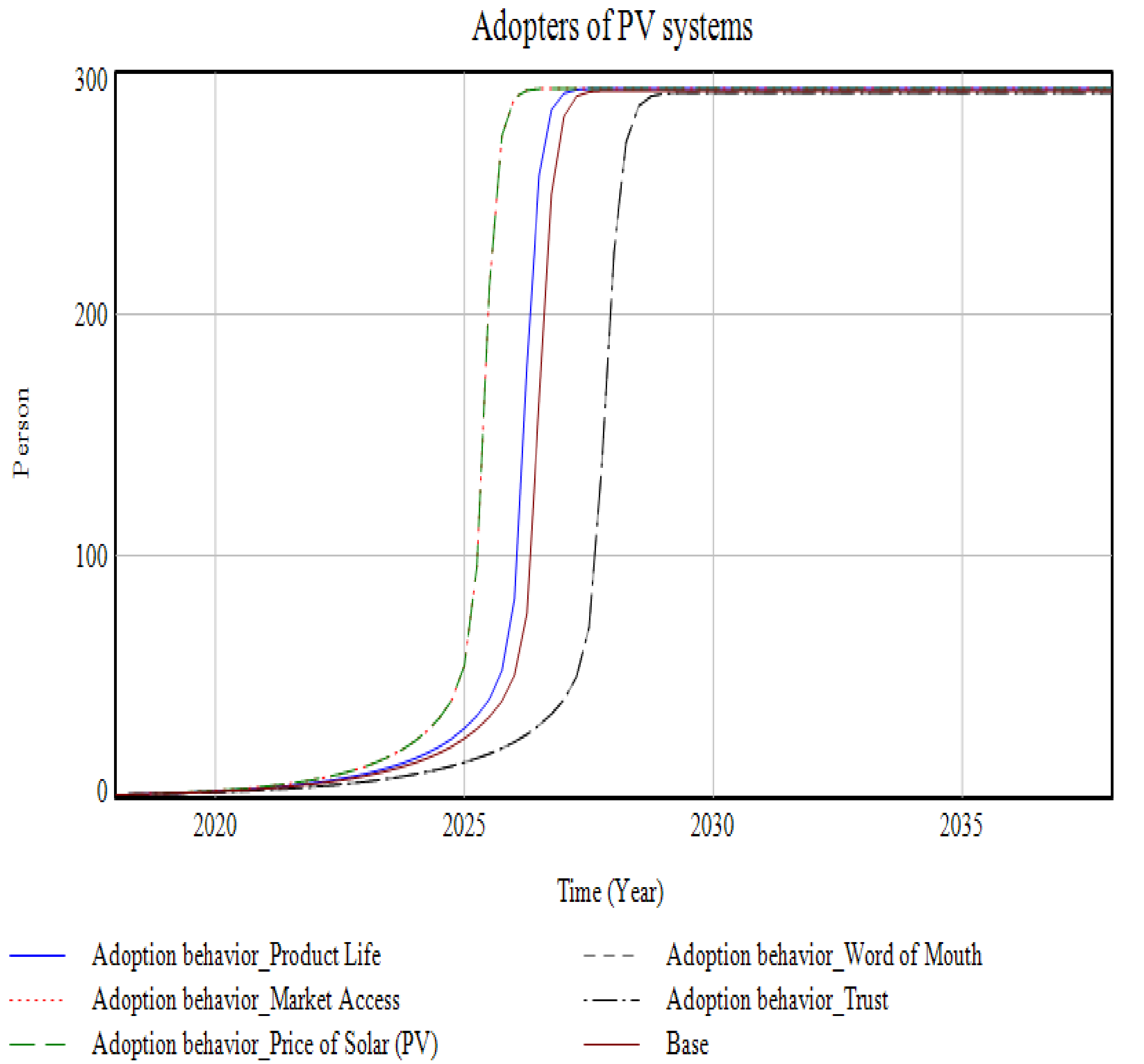

Figure 3.8: Differences in Adoption behavior with selected parameters changed one at a time by -10%. The changed parameter is indicated after the underscore

3.5.3 Sensitivity analysis: Solar Chargers

Figures 3.9 and 3.10 illustrate the diffusion curves for adoption of Solar Chargers. In the base case, the adoption for solar chargers peaks earlier than PV systems at around 3 years. There is slow adoption in early years, then it rises quickly after 2 years. We conducted similar analyses as shown above on selected parameters changed by ±10%. The simulation of selected parameters at +10% shows that the variables trust, word of mouth, and price of solar had the most effect on increasing adoption. Market access and product life had the least impact on the speed at which all households adopt off-grid solar chargers. The simulation of selected parameters at -10% for solar chargers shows that the variables: product life and market access had the most effect on increasing adoption. Trust, price of solar chargers and word of mouth have the least impact on household adoption. Changes made to select parameters did not significantly alter the model over time.

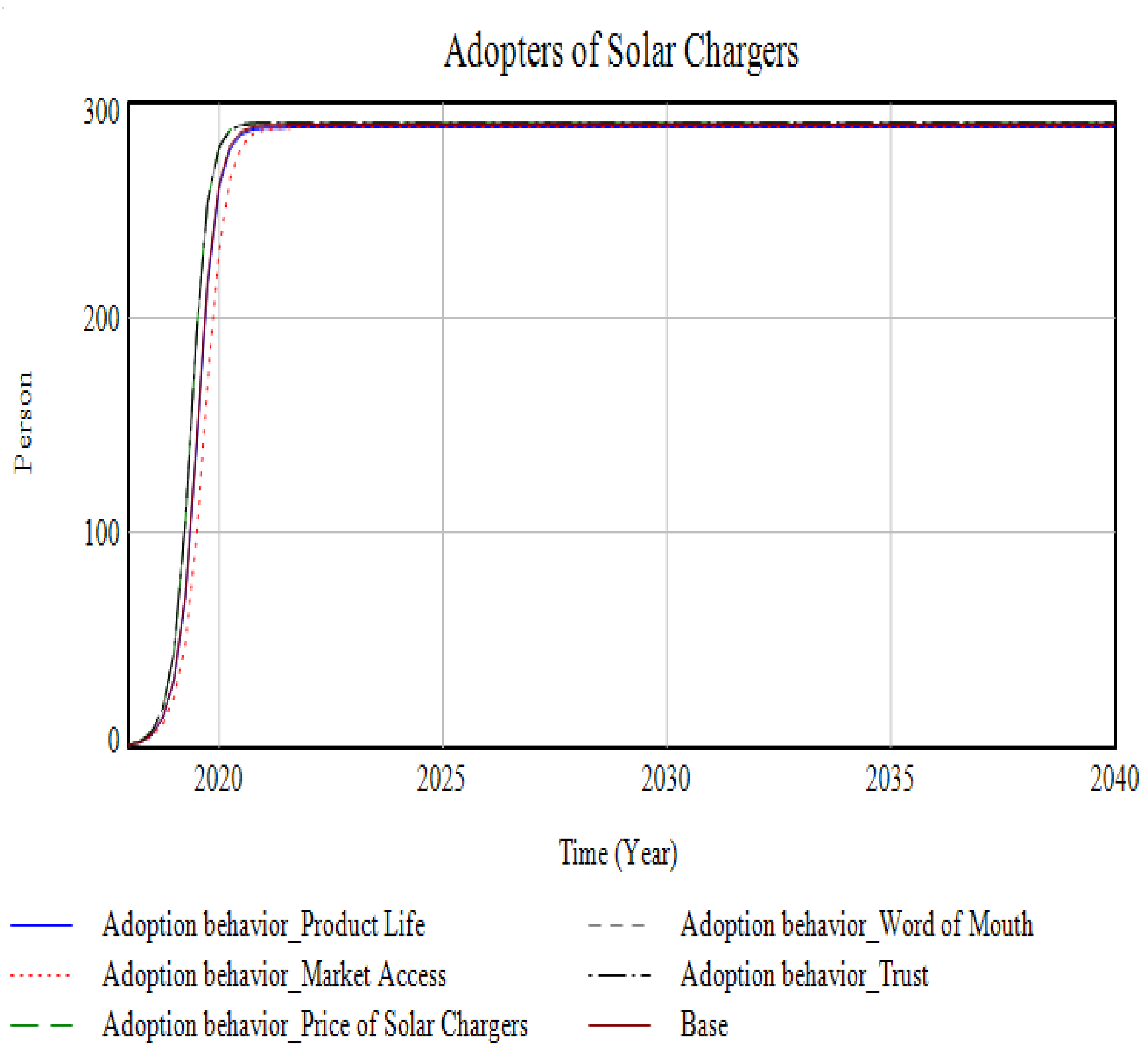

Figure 3.9: Differences in Adoption behavior with selected parameters changed one at a time by +10%. The changed parameter is indicated after the underscore

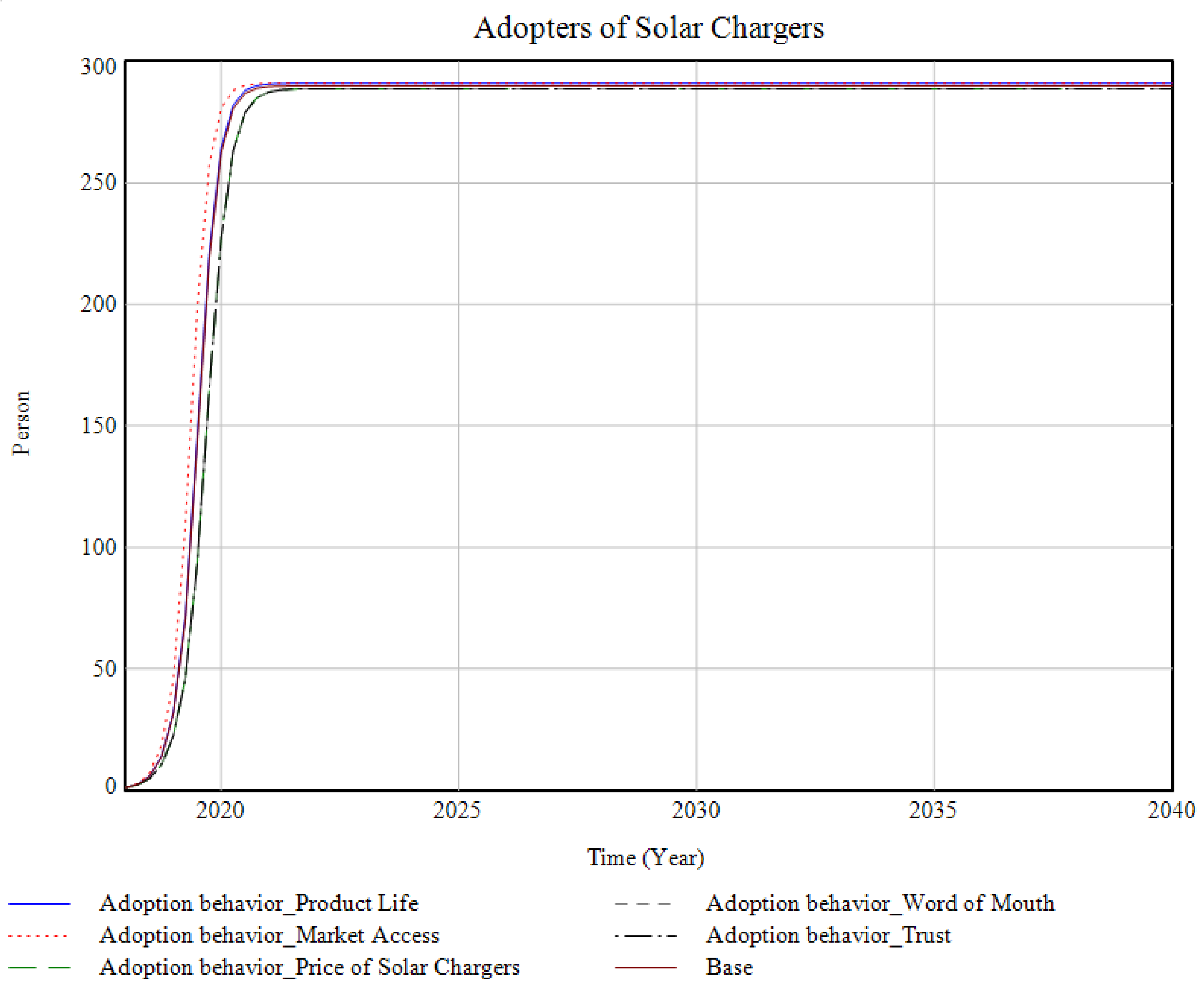

Figure 3.10: Differences in Adoption behavior with selected parameters changed one at a time by -10%. The changed parameter is indicated after the underscore

3.5.4 Scenario Analysis

Table 3.1: Description of selected scenarios

Scenario	Description of parameters
Base case	Base case (model with initial values)
Scenario 1 (Price and government policy)	Price for off-grid solar is reduced by 30%. All other parameter values are held at their base values.
Scenario 2 (Trust)	Trust by consumer is increased by 20%. All other parameter values are held at their base values.
Scenario 3 (Product life)	Effect on the consumer is decreased by 20%. All other parameter values are held at their base values.
Scenario 4 (Market Access)	Distance to the market decreased by 50%. All other parameter values are held at their base values.

In the first Scenario, the price decrease appears to provide benefits to households that want to adopt PV systems, because the results indicate households adopt PV systems more rapidly under this scenario than the Base case. However, for solar chargers, fewer households adopt when the price of solar chargers decreases; as compared to the base case about 5% fewer households adopt. Since the households are not completely familiar with the product and brand, they use price as a cue for the quality and attribute higher quality to price. This means the products are not equal in the eyes of the consumer because they assume because the price is higher, the quality is better. In addition, because of their negative perception of solar products on the market and risk of product not working, households select higher priced products (Zeithaml, 1988). This behavior is entirely consistent with the psychology and marketing literature, along with results from survey and choice experiments (Bagwell & Riordan, 1991; Chapter 2).

For the second scenario, our results suggest that there is an increase in adoption when consumers trust the technology more. When suppliers provide warranties for the product, it could improve adoption and increase competition. As seen in the third scenario, product life appears to drive adoption for both PV systems and solar chargers, in that less of an effect of product life suggests a positive impact on adoption. It follows that households want better products that they can use for longer periods of time. The fourth scenario suggests that market access stimulates the most rapid adoption for both PV systems and solar chargers to households through shorter distance to market. Increase of suppliers of off-grid solar electricity that are closer to households would have a positive effect because more people would have easier access to the technology. If all scenarios are accompanied with other policy mechanisms like reduction in import taxes, price subsidies and stronger regulations on product quality, adoption of off-grid solar electricity within Nigeria could be made more rapid.

An important reflection is that access to electricity for households can be improved much faster with support from the government and better policies that can drive growth, and an environment that is suitable for markets and foreign direct investments from off-grid solar electricity companies. The results from all scenarios are shown in figure 3.11 and figure 3.12. They indicate that households will continue to increase their adoption of off-grid electricity if they have favorable market access, better quality, trust in product, lower prices in for PV systems and higher prices for solar chargers.

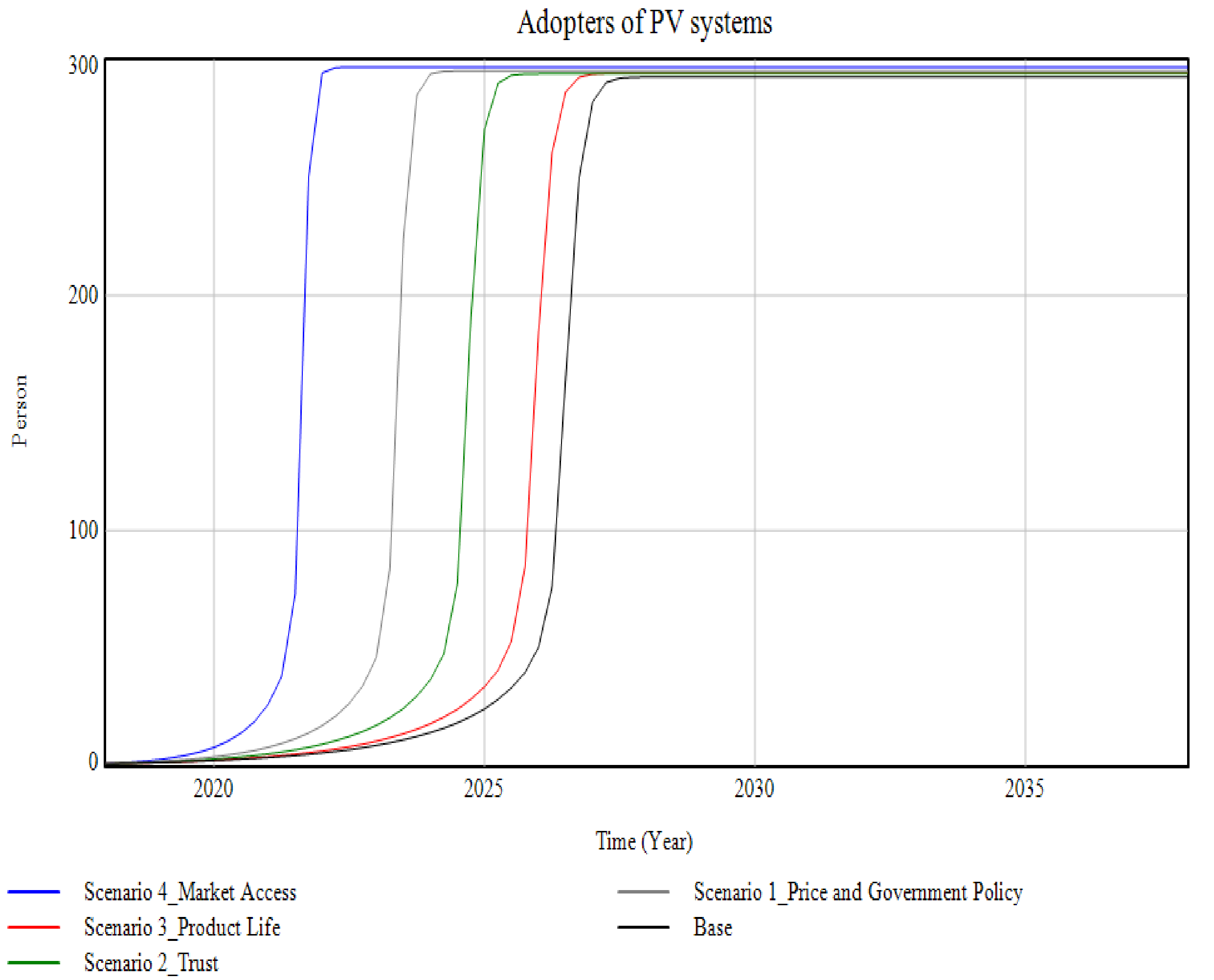

Figure 3.11: Adoption Behavior of selected variables for PV systems under different scenarios

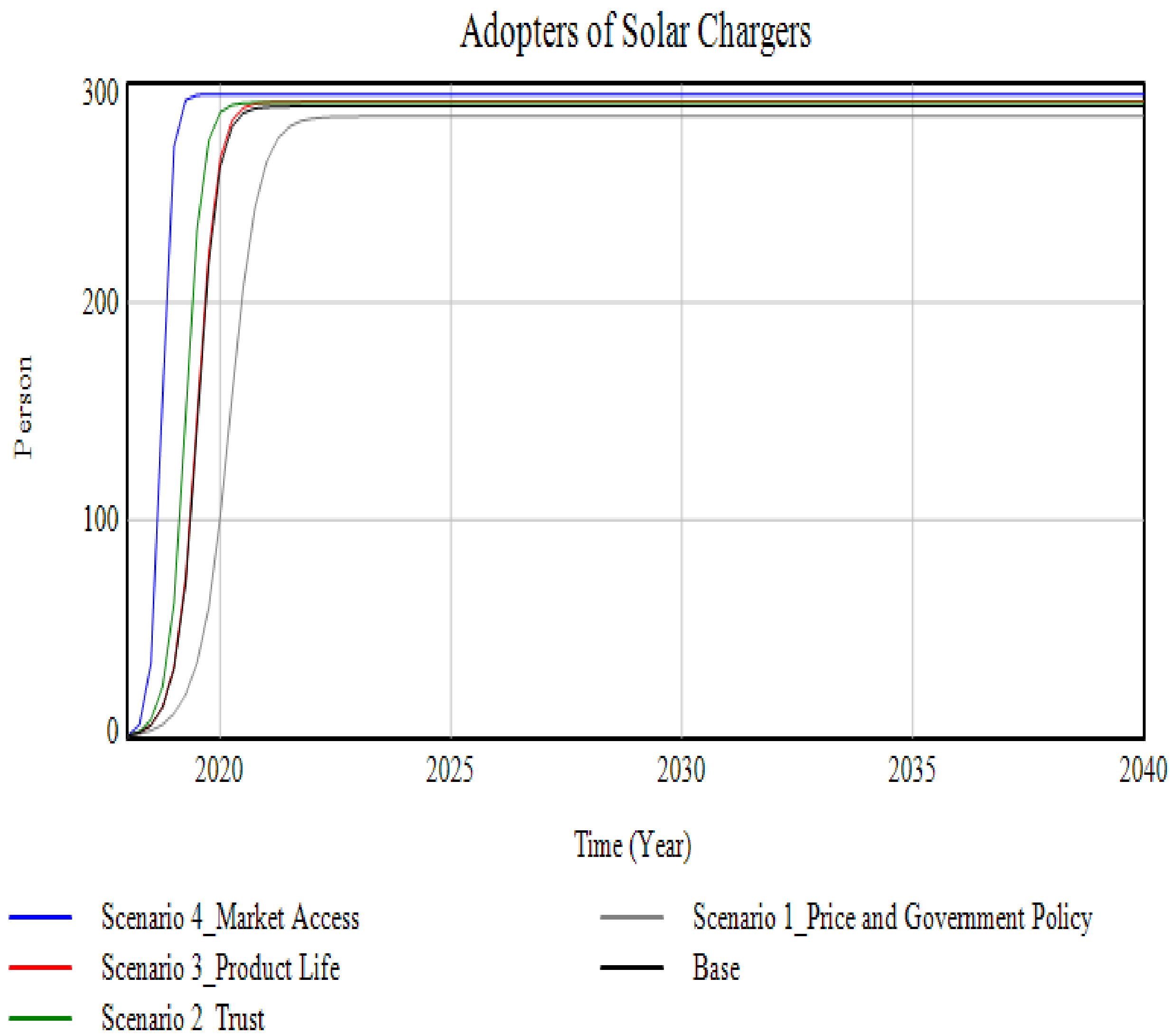

Figure 3.12: Adoption Behavior of selected variables for Solar Chargers under different scenarios

Given the conditions of access to electricity in Nigeria, it is important that policy makers understand that subsidies or tax cuts, without policies that improve the quality of the products and market access, would not create sustainable adoption of off-grid solar electricity.

We illustrate the impact of combined scenarios on adoption and also the contrast. The adoption of PV systems picks up drastically and hits optimum levels after 2 years when all scenarios are combined as compared to the base case peak adoption timing of 10 years, and adoption is close to Zero when the interventions described in the scenarios are reversed (Figure 3.13). The adoption of solar chargers picks up rapidly also by 2 years when all scenarios are combined, as compared to the base case of 4 years, and slows adoption to 6 years when the interventions described in the scenarios are reversed (Figure 3.14). Both figures show households exhibit strong adoption behavior to solar chargers than PV systems.

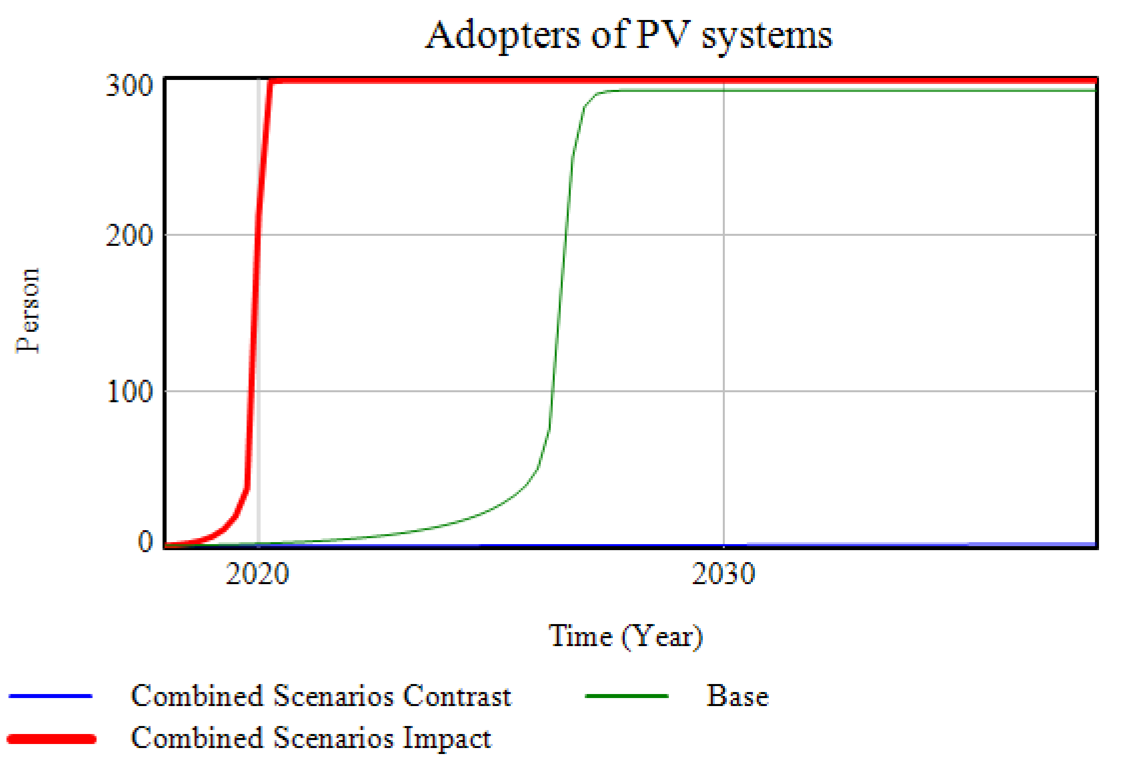

Figure 3.13: Combined scenarios impact and contrast for PV systems

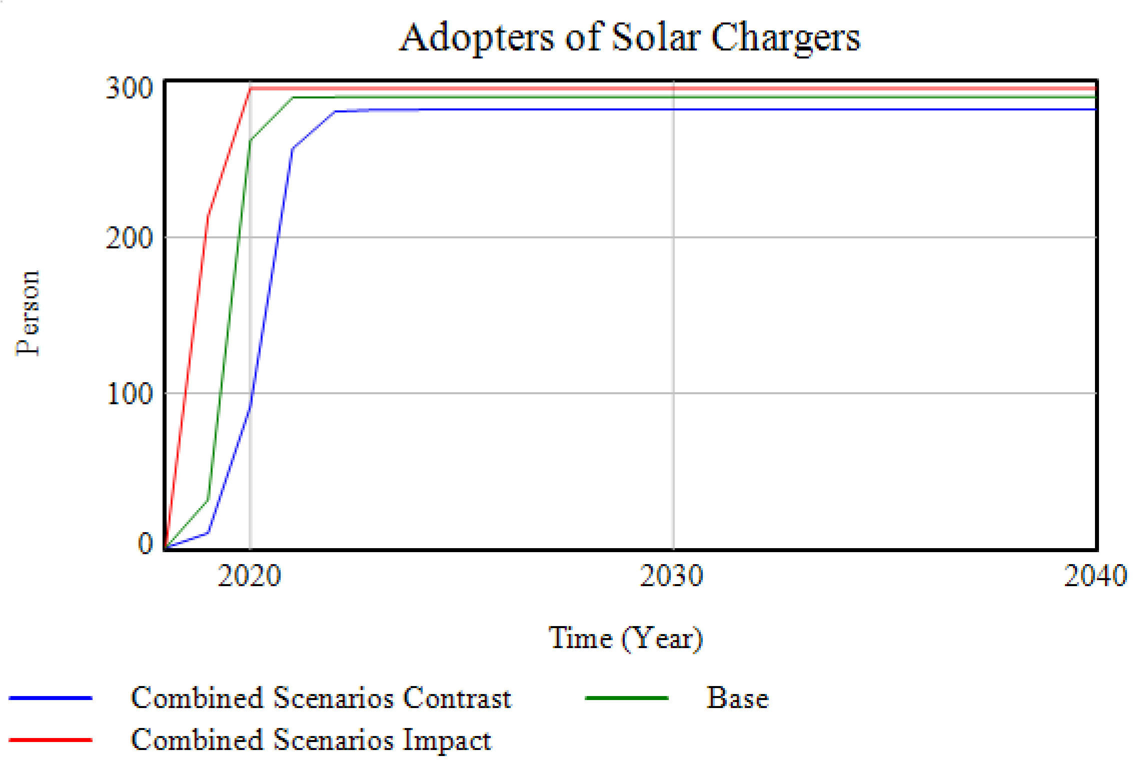

Figure 3.14: Combined scenarios impact and contrast for Solar Chargers

In addition, manufacturing in Nigeria by American companies can cut prices and create jobs, using local resources and redesigning off-grid solar technology to meet the needs of the population. Overall, the results presented in this study can contribute to policy that will help develop electricity access and adoption in Nigeria

3.6 Conclusion

Solar electricity companies understand there is a need for off-grid solar electricity, but they face an uncertain, complex and dynamic environment in the Nigerian market. The factors that affect the market change over time, and adoption behavior is not always known at the time companies are deciding to enter the market. One method companies can use to explore the effects of different decisions and factors that affect adoption is the use of system dynamics modeling. This method incorporates the complexities of the environment and presents information in a way that it is easy to understand.

The system dynamics model created and used in this study is a model of household adoption of off-grid solar electricity. The model used feedback effects and dynamic causal factors to provide insights to solar electricity companies on adoption behavior in the Nigerian market for off-grid solar electricity. The study also demonstrated how system dynamics can be used to evaluate and maximize adoption of technologies (Fisher et al., 2000).

APPENDICES

APPENDIX

Table 3.2: Variables and Parameter values in the model

Variable	Values	Comment/Description
Distance to market	120 miles	Distance from Ayetoro to Lagos
Market Access	1/120	Fraction determines the ease of market access
Effect of Electricity Bill	Dynamic	Price increases every year by 5%
Alternatives for Electricity	Dynamic	Ratio of Price of generator to Solar
Price of Generator	$270.00	Average price for generators with 2.02 KVA capacity
Price of PV systems	Dynamic	Price goes down over time
Word of mouth	Adopters off Grid/Total population	Word of mouth from households
Interactions between Potential adopters and adopters	Perception of technology* mouth of word from adopters	Perception of technology from potential adopters and mouth of word from adopters
Perception of technology	Potential Adopters * Trust	Trust and Potential adopters
Initial Population	300	Number of households surveyed
Trust in technology	0.71	70% reported that trust the technology
Consumer preference	Trust	Trust influences consumer preference for technology
Product Life	Dynamic	Effect of product life on consumer decisions
Total population	Potential Adopters + Adopters of off-grid solar electricity	
Price of Solar chargers	Dynamic	Initial price is $15 but it will decrease over time
Households	121	Number of households in Energy survey
Electricity cost per unit from grid	Dynamic	Effect of electricity cost over time
Improvement on product life	Dynamic	Product gets better as improvements as made over time

REFERENCES

REFERENCES

Aliyu, A. S., Ramli, A. T., & Saleh, M. A. (2013). Nigeria electricity crisis: Power generation capacity expansion and environmental ramifications. *Energy*, *61*, 354–367. https://doi.org/10.1016/J.ENERGY.2013.09.011

Bagwell, K., & Riordan, M. H. (1991). High and Declining Prices Signal Product Quality. *The American Economic Review*, *81*(1), 224–239. Retrieved from http://www.jstor.org/stable/2006797

Bass, F. M. (2004). Comments on "A New Product Growth for Model Consumer Durables The Bass Model." *Management Science*, *50*(12_supplement), 1833–1840. https://doi.org/10.1287/mnsc.1040.0300

Breierova, L., & Choudhari, M. (2001). *An Introduction to sensitivity analysis*. Massachusetts Institute of Technology.

Candelise, C., Winskel, M., & Gross, R. J. K. (2013). The dynamics of solar PV costs and prices as a challenge for technology forecasting. *Renewable and Sustainable Energy Reviews*, *26*, 96–107. https://doi.org/10.1016/J.RSER.2013.05.012

Chidebell-Emordi, C. (2015). The African electricity deficit: Computing the minimum energy poverty line using field research in urban Nigeria. *Energy Research & Social Science*, *5*, 9–19. https://doi.org/10.1016/J.ERSS.2014.12.011

De Marco, A., Cagliano, A. C., Nervo, M. L., & Rafele, C. (2012). Using System Dynamics to assess the impact of RFID technology on retail operations. *International Journal of Production Economics*, *135*(1), 333–344. https://doi.org/10.1016/J.IJPE.2011.08.009

Fisher, D. K., Norvell, J., Sonka, S., & Nelson, M. J. (2000). Understanding technology adoption through system dynamics modeling: Implications for agribusiness management. *International Food and Agribusiness Management Review*, *3*(3), 281–296. https://doi.org/10.1016/S1096-7508(01)00048-9

Ford, A. (2010). *Modeling the Environment* (Second). Island Press.

Guo, H. C., Liu, L., Huang, G. H., Fuller, G. A., Zou, R., & Yin, Y. Y. (2001). A system dynamics approach for regional environmental planning and management: A study for the Lake Erhai Basin. *Journal of Environmental Management*, *61*(1), 93–111. https://doi.org/10.1006/JEMA.2000.0400

Hekimoğlu, M., & Barlas, Y. (2010). Sensitivity analysis of system dynamics models by behavior pattern measures.

International Energy Agency, I. (2017). *Energy Access Outlook 2017 (from Poverty to Prosperity)*. Retrieved from http://www.iea.org/publications/freepublications/publication/WEO2017SpecialReport_EnergyAccessOutlook.pdf

Kotir, J. H., Smith, C., Brown, G., Marshall, N., & Johnstone, R. (2016). A system dynamics simulation model for sustainable water resources management and agricultural development in the Volta River Basin, Ghana. *Science of The Total Environment*, *573*, 444–457. https://doi.org/10.1016/J.SCITOTENV.2016.08.081

Nigerian Electricity Regulatory Commission. (2018). Electricity: Generation, Transmission, Distribution and Market Financial. Retrieved March 6, 2018, from http://www.nercng.org

Nigerian Electricity Regulatory Commission (NERC). (2017). NERC Third Quarter Report 2017. Retrieved July 27, 2018, from http://www.nercng.org/index.php/component/remository/NERC-Reports/NERC-Third-Quarter-Report-2017/?Itemid=591

Nouni, M. R., Mullick, S. C., & Kandpal, T. C. (2008). Providing electricity access to remote areas in India: An approach towards identifying potential areas for decentralized electricity supply. *Renewable and Sustainable Energy Reviews*, *12*(5), 1187–1220. https://doi.org/10.1016/J.RSER.2007.01.008

Rogers, E. M. (1976). New Product Adoption and Diffusion. *Journal of Consumer Research*, *2*(4), 290. https://doi.org/10.1086/208642

Rogers, E. M. (2010). *Diffusion of innovations*.

Rural Electrification Agency. (2018). Catalysing the off grid market to increase electricity access to rural and underserved communities through public & private sector engagement. Retrieved November 17, 2018, from http://rea.gov.ng/

Sahin, O., Stewart, R. A., & Porter, M. G. (2015). Water security through scarcity pricing and reverse osmosis: a system dynamics approach. *Journal of Cleaner Production*, *88*, 160–171. https://doi.org/10.1016/J.JCLEPRO.2014.05.009

Sambo, A. (2008). Matching electricity supply with demand in Nigeria. *International Association for Energy Economics*, (4), 32–36. Retrieved from http://expertscolumn.com/content/matching-electricity-supply-demand-nigeria

Sterman, J. (2000). *Business dynamics: systems thinking and modeling for a complex world*.

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, *108*(50), 20260–20264. https://doi.org/10.1073/pnas.1116437108

Unachukwu, G. O. (2010). Energy savings opportunities at the University of Nigeria, Nsukka. *Journal of Energy in Southern Africa*, *21*(1), 2–10. Retrieved from http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1021-447X2010000100001&lng=en&nrm=iso&tlng=en

Zeithaml, V. A. (1988). Consumer Perceptions of Price, Quality, and Value: A Means-End Model and Synthesis of Evidence. *Journal of Marketing*, *52*(3), 2. https://doi.org/10.2307/1251446