Determinants of Solar of Panel Adoption, Disadoption and Use in Malawi

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Abstract

Malawi has one of the lowest rates of electricity access in the world with high rates of blackouts due to reliance on a hydropower system whose capacity is adversely affected by droughts and flooding. There has been a push to expand electricity access with solar energy seen as a sustainable path, particularly in rural settings. We use four waves of the nationally representative Malawi Integraged Household Survey (IHS) spanning the period 2010 to 2020 to examine determinants of household adoption and disadoption of solar panels. Specifically we explore trends in adoption, what energy services households are using solar panels for, characterisics of households who adopt, and from among those who adopt, who is likely to disadopt. Between 2010 and 2020 household adoption of solar panels increased from 1.2% to 19.5%, with higher rates of take-up in rural settings (21.7% by 2020) compared to urban settings (9.8% by 2020). Among those who adopt solar panels, fewer than 1% of households report using solar for lighting, suggesting that solar adoption does not necessarily equate to provision of lighting services. We find the households most likely to adopt solar panel are in rural areas, are male headed, own a mobile phone, and own a tv or radio. Policy makers seeking to improve energy access should consider not only uptake of solar panels but also patterns of use and reconsider the assumption that rapid solar uptake will lead to provision of lighting services, a key dimension of household energy access.

Introduction

In 2015, the United Nations initated the Sustainable Development Goals and included Goal 7, ensuring clean energy for all (UN 2015). Providing access to clean energy is one of the best ways to improve livelihoods as clean energy has the potential to improve food and water availability, reduce poverty, improve health, raise living standards, and decrease gender inequalities (IEA 2022 and WHO 2014). Traditionally, increasing energy access means expanding the electrical grid system of countries. There has been some progress in achieving SDG 7 as the world has seen an increase in electricity access over the last few decades (IEA 2022).

Still there is a lot of work to be done in achieving SDG 7. Currently, there are 770 million people in the world who do not have access to electricity (IEA 2022). The onset of the COVID-19 pandemic has only made the situation worst and has threatened the transition to modern energy (IRENA 2021). In Africa specifically, gains in electric grid access have been set back by the onset of the pandemic. Approximately 30 million people across the continent are no longer able to afford electricity due to economic hardship during the pandemic (IRENA 2021). On the other hand, renewable energy has emerged as a resilient approach to improving energy access through COVID-19 (IRENA 2021). The declines in energy access during the pandemic were not seen in decentralized systems like solar mini-grids and off grid systems and other solar technologies (IRENA 2021).

Africa is primed for solar, having one of the highest photovoltaic (PV) solar potentials in the world (IRENA 2022a). The average African country has a significantly better photovoltaic (PV) potential than most European countries (World Bank 2020). In turn policymakers have increased efforts to promote solar technologies across frica and the continent has seen a growth in household's adopting solar technologies (Ojong, 2021). Solar home system sales increased in SSA from a half a million units in 2011 to 11.3 million units in 2015 (Ojong, 2021), accounting for 70% of total global solar home system sales. The International Renewable Energy Agency (IRENA) points out the benefits of SHS such as lighting, cell phone charging, or powering televisions and radios at prices lower than other modern energy sources (IRENA 2022b).

With the rise of solar home systems in the continent, this paper examines trends and determinants of household solar panel adoption and disadoption between 2010 and 2020. The paper uses four waves of data from the Integrated Household Survey (IHS) to focus on Malawi, a small country in Southern Africa with the lowest electricity access rate in its region (World Development Indicators 2018). This study examines solar panel adoption and use from the survey question "does the household own a solar panel?". For the purposes of this study, a solar panel includes any system in a house that uses a panel such as lights or home systems. The paper address gaps in the literature as it is one of a few studies that looks at solar panel adoption across urban and rural areas, uses panel data, and studies disadoption of solar panels.

2. Literature Review

Energy Transitions:

Energy ladder and fuel stacking hypothesizes

Household energy transitions have been studied for decades. The initial framework for transitions is the energy ladder hypothesis, where households move in a linear path from traditional energy sources to new cleaner sources of energy as income increases (Hosier &Dowd 1987). A competing energy transitions paradigm that came after the energy lader is the fuel stacking paradigm where households shift to cleaner sources of energy but still use traditional sources, thus stacking their energy sources (Leach 1992 and Heltberg 2004). An example of this in lighting is a house with a solar lamp may still use candles and kerosene to meet their lighting needs (Heltberg 2004). Reasons why people switch from one source to another is more complex than just economics, factors such as convenience, culture, and tradition also play important roles in household's fuel choice may lead to fuel stacking or the energy ladder(Hosier & Dowd 1987 and Leach 1992).

Energy transitions are not always equal. Nguyen et al. (2019), studied energy transitions in rural Vietnam. They found an energy transition occurring, but it is inequal in nature with poor households and ethnic minority households lagging behind as more affluent and ethnic majority households modernize first. On the other hand, energy transitions can improve marginalized sub-populations' livelihood, especially women, infants, and children (Boateng et al. 2020). Energy transitions in urban and rural areas look different. Such as for a general popultaiton, lighting makes up 10-20% of energy consumed in most countries the fuel source may differ for urban and rural areas (Dutt, 1994). Balachandra (2011) saw that biomass is the main source of energy for cooking in rural households while kerosene is the main source for lighting. However urban households see a different trend where kerosene is the major energy source for both lighting and cooking and biomass is only used in a minor amount (Karakezi et al 2008).

As Malawi modernizes, solar is expected to be fundamental to the energy transition, charting a energy path unique to Malawi(Sokona et al. 2012). Elias and Victor (2005), show a transition that moves from basic needs such as lighting, education etc. supplied by modern fuels to an energy sector that can meet modern needs and appliance use. As a household gains access to electricity, especially in rural sub-Saharan Africa, initial access leads to further household demand for electricity, such as access to lighting leads to demand for appliances to TVs then stereos then fridges, etc. (Opiyo, 2020). The connection though is that the energy transition will start with productive uses of modern fuels in agriculture, commercial, and transportation sectors before households modernize their energy sources (Opiyo, 2020).

Solar Adoption

Adoption

Adoption of solar seems to be a question of tradeoffs for the households. The competing reasons found to adopt a solar system in rural areas were mobile phone charging, radio and TV access, and lighting (Ulsrud et al, Ondraczek 2013). The systems sold rarely support all of these uses at once so all these uses compete with each other and lighting is a secondary option when acquiring a solar system (Jacobson 2007, Bleeker 2013). As such, the driving forces in places such as in Kenya, are tv and radio for solar adoption, instead of lighting (Stojanovski et al 2017). These areas are typically not connected to the grid, and such rural areas have had higher uptake of solar than urban (Ondraczek 2013). However, there is evidence that early adopters, ie. when the technology are new, may have different adoption trends. A study in Tanzania looked at early adoption in 10,000 households in the 2007 Tanzaninan National Household Budget Survey and found that early adopters of solar were more rural and used solar as a back up lighting source to the grid (Smith and Urpelainen 2014). Still, a population of high-income households make up the energy elite who use these systems for lighting, mainly as a backup source during grid blackouts (Boamah and Rothfuß 2018).

There are efforts to help low income households adopt solar .Subsidies and cash transfers are both effective means to increase the affordability of solar technology (RP Clarke 2019, Pachari et al. 2013, Komives et al 2007, Aung et al 2021). Subsidies can lead to increases in solar uptake (RP Clarke 2019). Futher subsidies lead to increased choice of fuel and energy access in poor households (Nawaz and Igbal 2020). Sovacool (2014) though points out that while these programs help improve energy access, they do not always help or target the ultra-poor. More often than not, the ultra-poor do not benefit the most from energy programs and instead end up getting left behind. Aung et al. (2020) find that ultra-poor households experience much greater energy poverty than better off households, however if a subsidy program targets ultra poot households then these housegolds can see improved energy access for the ultra-poor including solar.

There are a number of barriers to adopting solar technologies at various levels. Girardeau et al (2021) performed a systematic review of papers focused on barriers and drivers of solar adoption. The authors grouped barriers and drivers of adoption into four groups (finance barriers, market ecosystems, regulations, and program tools). The authors examined how individual papers either found specific barriers or drivers for solar adoption in each group. As statetd above, financial programs like subsidies or loans can be strong drivers for solar technology adoption while upfront cost of the system can be a barrier for a household to adopt (Girardeau et al 2021). In market ecosystems group, marketing and promotional efforts are the net drivers of adoption while factors like product quality and the culture of the community to largely be barriers for adoption (Girardeau et al 2021). Regulations were net drivers in large where policy and laws that benefit solar technologies adoption (Girardeau et al 2021). Similar to market ecosystems, program tools were majority net barriers for adoption with quality control and consumer awareness being the main barriers for adoption studies and aspects such as gender and solar adoptuion are not widely studied (Girardeau et al 2021).

Mensah and McWilson (2021) examined the characteristics of households that adopt solar. They found education, income levels, performance expectations, and housing tenure arrangements were crucial factors in households adopting SHS. Further characteristics affect household adoption and use. Gender is found to interact with age and geographical location in adopting SHS across sub–Saharan Africa (Mensah and McWilson 2021). Adopting these SHS may reenforce the power structures already existing in these communities. Such as in married houses, husbands often chose the physical location of SHS light bulbs such that it benefits them in their activities and not in ideal locations such as kitchens.

Increased access to energy is important to improving the economic status of the households. Chakravarty et al. (2008) saw that electrifying rural areas leads to meaningful gains in households' income, especially in agricultural households. This was true with light as well as, Hanna and Olivia (2015) found that increasing lighting from electricity saw households rise in economic status. An increase in energy and improving household wellbeing is more relevant today during the COVID-19 Pandemic. Zaman et al. (2020) found that during a pandemic, solar energy safety nets ran by different countries allowed poor households to better prepare for, respond to, and recover from the global pandemic's effects. The off-grid solar systems in these projects were crucial for households to improve their resilience. These solar systems allowed these households to practice better protective actions like staying at home and social distancing as the household members did not have to travel outside of their houses to do things like charging their phones, even in Malawi.

Use

Examining how people use solar home systems in lower and middle income countries is fairly homogenous. Gustavsson 2004 showed early on that people used solar systems for entertainment appliances like TVs or radios or for lighting the household. There was interest in using solar for other appliances such as stoves, irons, or fridges but these appliances were either costly or infeasible at the time (Gustavsson 2004). The rise of mobile phones changed solar use as mobile phones were not around at the time of Gustavsson's 2004 study. Bisaga and Parikh study solar use in Rwanda in 2018. By this time mobile phones were more widespread and the two main uses for solar were lighting and mobile phone charging. There was also some evidence that people used solar systems as back ups if the houses were well off and connected to the grid (Bisaga and Parikh 2018). Diallo and Moussa 2020 also saw that tvs, radios, mobile phone charging, and lighting are all driving factors for adopting solar home systems and that owners of these systems owned more phones, radios, and tvs. Solar use seems to be complex and dynamic and vary over time.

Solar home systems adoption and usage in low to middle-income countries is poorly understood. Stojanovski et al. (2017) interviewed 500 early adopters of SHS in Uganda and Kenya. Early adopters were defined are adopters of SHHS where they technology is relativelyn new They found that SHS usage is associated with large reductions in kerosene use and mobile phone charging and the systems were not used to power radios, TVs, or flashlights. Lighting was the primary use but a problem with these systems was the small amount of wiring provided with the systems lead to lighting not being used optimally throughout the whole house. Conerserly a paper looking at urban and rural population of early solar adopters in Tanzania found that adopters were mostly urban and used solar panels for back up lighting during blackouts (Smith and Urpelainen 2014).

Solar adoption is mostly measured by ownership of a system or panel. For example, in a study using one wave of a household survey in Tanzania, adoption of solar technologies is defined as owning a solar panel (Smith and Urpelainen 2014). Another study examining early adopters defined solar adoption as buying a solar home system and defined use based on reported lighting sources and calculated use through surveys and questions such as where do they charge their cell phone (Stojanovski et al 2017). Again a study in Rwanda defined adoption by ownership however the adopters were placed into groups based on the length of ownership to determine solar panel use based on length of ownership (Bisaga and Parikh 2018).

Disadoption

Disadoption is not widely studied but there are theoretical works on why disadoption happens. Alpizar et al in review though is examing disadoption through a theoretical framework of technological use and case studies. There are four steps for use where a household first acquires a technology, then uses the technology, then either continues to use it which is called sustain use or disadopts the technology (Alpizar et al in review). Three influencing factors for households in whether they move to systaun use or disadopt are information on benefits, ability to maintain the technology, and taste or preference for the technology (Alpizar et al in review).

The model can be applied Alpizar et al worked on can apply to other studies that look at factors of disadoption. Such as in Uganda, disadoption of biogass digestors was caused by a failure to sustain a fuel source such as cattle or pigs and inability for households to repair bio digestors (Lwiza et al 2017). Both fuel source and inability to repair reflect the household's ability to adopt the technology. Another study in Ethiopia follows this Study. A population in urban Ethiopia disadopted electric cookstoves from 2000-2009 due the household's economic status and price of electricity (Alem et al 2013). This falls again into Alpizars et al's frame work, economic status and price of electricity can fall into a consumer's ability to maintain and use a product. As their status and price change, the stove could become unaffordable and the household no longer has the ability to maintain the stove.

Gaps

This paper addresses several gaps in the literature in solar adoption and LMIC. Little has been written on the topic of who adopts solar in Malawi and why. The prevailing theory is that people adopt solar for lighting. We examine who adopts solar, for what use, and whether these findings match with the wider narrative of solar as a primary source of lighting services in sub Saharan Africa. Few studies use panel data to examine determinants of adoption. Nor are there many studies that look at both rural and urban populations. Lastly this study looks at disadoption in solar which is also understudied.

Methods

Malawi

Malawi is a landlocked country in southern sub-Saharan Africa with one of the lowest GDPs per capita in the world (World Bank Indicators 2018). The population of over 19 million people is spread across 28 districts, with most of the population living in the Southern Region (UN World Population Prospects, 2019). The energy access rate in Malawi is low with 37% of urban households and 2% of rural households connected to the grid (ACE 2021). Rural populations rely largely on biomass to meet household energy needs, especially for cooking (Aung et al 2021). For lighting though, the majority of rural houses do not use biomass but instead rely mostly on battery torches, kerosene lamps, or candles as their main source of lightin (Aung et al 2021). However, over the past decade there have been significant efforts by the Government of Malawi, donors and the private sector to increase electrification through decentralized grid projects and the promotion of solar. Specifically the Government of Malawi has signed the Malawi Cleaner Cooking Energy Compact to move towards achieving SDG 7 in the country (GoM 2021). While the main emphasis of this compact is on clean cooking technologies, target 7.2 specifcally talks about "increase[ing] substantially the share of renewable energy" and provide more investments into solar electricity generation (GoM 2021).

There is a robust market for solar with over 20 firms operating in the country (Appendix A1). The most popular business model is pay as you go (PAYGO) where customers place a deposit on a solar home system and then pay either daily, weekly, or monthly payments on the system until they own it. These systems are simple, usually consists of one panel, several lights, and phone charging capabilities but more extensive systems are available. More extensive systems are sold more lights, radios, television, fans, and some cooling. From the base model sold, it is easy to assume that most people use solar for lighting.

Integrated Household Survey (IHS) data

The data for this thesis is from the Malawi Integrated Household Survey (IHS). The IHS is a population representative survey that has been implemented six times starting in 1997. Households are selected to represent the national, regional, and urban/rural populations. Starting in 2010 in the third survey, with funding from the World Bank, the IHS began incorporating a panel as a subset of the data. Panel data follows the same household over multiple time periods. Households in the panel sample were surveyed four times (2010, 2013, 2016, and 2020). The break down of households in each wave can be seen in Table 1. We use this subset of households in my analysis because we are interested in observing household characteristics that increase the chances of adopting solar. An analysis of panel data which looks at the same households over multiple years as they adopt and disadopt solar allows us to assess causal factors driving adoption while minimizing estimation biases compared to the cross-sectional data. Further, using the panel dataset allows us to track which households disadopted solar and provide an analysis of the determinants of disadoption of solar.

Table 1. Sample sizes of each wave of data collection for full and panel datasets in Malawi's Integrated Household Survey

Year	Full Dataset	Panel Dataset
2010	12,271	1,017
2013	1,990	1,017
2016	12,447	1,017
2020	11,434	1,017

*2013 is much lower since that wave prioritized collecting data for the panel dataset only

The data for this thesis comes from the World Bank. It is deidentified and available on request on the world bank website (https://microdata.worldbank.org/). The data was used with the permission from the World Bank and the National Statistics Office of Malai under the purview of the University of North Carolina, Chapel Hill Institutional Review Board.

Sampling for the Panel

The first wave of the panel collected in 2010 included 3,104 households located in 204 enumerated areas. In the secondwave (2013) it was decided to track all individuals in the baseline household, even if they moved from the household. This increased the observation size of wave two to 4,000 households. In 2016, due to budget constraints, the number of EA's were reduced in half to 102. EAs were excluded to ensure the proper proportional allocation of region, urban, and rural households matched that of the wave 1. In 2019-2020 survey, the survey team interviewed the same household as were interviewed in 2016.

The addition and removal of households between 2010 to 2016 made it difficult to track the same households across each wave. Individuals that were followed were given the same household id as their original household. This created an issue with following households and ensuring that the same household was measured across each year. For example, if a household in the panel had five members and in 2013 one person left, the panel would follow the person who moved out and add their household to the panel with the same household ID. Thus it could happen that the same household ID represents two different households in 2013, regardless of whether the person who left moved within the same village or to another district or region.

For this analysis, we define a household as a group of people that reside (e.g., sleeping and eating under the same roof) together over time. . The extra households that were added to the sample do not meet this definition and are not part of the true panel. To create the true panel, we restricted the dataset to include households that had the same household head for all four waves of the survey. The survey gave each household member a unique id. If the household head was the household head for all four waves, then that household was retained. If the household head was not the household head for all four years, the observation was dropped. This strategy removed any households that were added to the survey in subsequent years, and removed any households where the household head changed or was no longer present . The final dataset has N=1,017 households present in each of the four waves. The breakdown of the households by region is North (N=126), Central (N=441), and South (N=450) for each wave and split by urban (N=269) and rural (N=748). The distribution of the panel dataset is similar to the full data set. The full dataset is 23% urban while the panel is 26% urban and by region households in the north make up 18.8% of the sample, central region households make up 34.7% of the households, and Southern Region households make up 46.5% of the population. The panel has higher representation from the central and urban regions than the full dataset but not by a significant amount as the panel is 9% more central and only 3% more urban.

Cutting the households from the panel to 1,017 did create some key differences in panel sample. We ran t-test to see if there were any significant differences between the houses that were cut and the houses that remained. Overall for most key variables we examine there were not significant differences. However in our panel, the household heads were nearly eight years older, had one more person in the household, and more likely to be male headed.

Analysis

Dependent variables

Our main independent variables are adoption and disadoption of solar panels. This is based on the survey question “does the household own a solar panel”. Thus adopt is defined as a house owning a solar panel and disadopt is defined as a house that had previously owned a solar panel but no longer owns a solar panel.

These dependent variables are binary variables where for adoption “0” means the household did not adopt a solar panel and “1” means the households did adopt a solar panel. Adoption is looked at in regression models in both the cross sectional data and the panel data. For disadoption, the binary variable is “0” for the household did not disadopt solar panel and “1” where the household did disadopt their solar panel. We can only look at disadoption through the panel data because the variable is deduced on whether the household previously owned a solar panel.

Independent Variables

The variables chosen for analysis come from an intensive literature review and inspection of the data. In other studies that examined household solar adoption, the most common variables in those models were household head age, household head education, household size, ownership of house, household head gender, energy expenditure, grid access, and urbanicity. The literature suggests that the use of solar home systems, especially small ones, are a tradeoff between tv or radio use, mobile phone charging, or lighting. Therefore, we decided to add both mobile phone ownership and tv/radio ownership to the model.

The models were run with variables both aggregated and disaggregated by housing quality and fuel expenditure. The fuel expenditure variable were only fuels that could be used for lighting sources in and a logged measure of how much the household spent on these fuels per week. The fuels were kerosene, fuel, candles, and expenditures and payments. One model has these expenditures disaggregated and the other model has the fuels added to a general lighting fuel expenditure variable. All expenditure variables were logged. For housing quality, the variables used were a roofing quality dummy variable (whether a house had iron sheets or not), wall dummy (whether the house had brick walls or not), and a floor dummy variable (whether the house had cement floors). The aggregated version of the housing variable is a dummy variable whether a house had all three housing quality variables or not.

The fixed effect of the region are also included in the analysis. In the cross sectional analysis the regions fixed effect is included in the model. In the panel data set, dummy variables for northern region, central region, and southern region were created to capture the fixed effects of these different regions and their impact on households adoption of solar.

Regressions were run using STATA/BE 17.0 . For the pooled cross sectional data, I used a multilevel mixed effect linear model to include fixed effects of region on the sample. For the panel data, the data was analyzed running logit models.

Descriptive Analysis

The analysis starts with looking at the descriptive story of solar panel ownership. We look at how adopters and disadopters compare to both each other and to non-adopters and to the dataset as a whole and identify key variables of who adopts and disadopts solar panels.

As there is not data on solar use besides lighting, solar use is solely a descriptive story. We look at how ownership of electrified technologies differ between adopters and non adopters. The main technologies we look are tv's, radios, and mobile phones. We also examine household primary lighting and blackout lighting to see if solar as a lighting ownership follows the same trend as solar ownership. Solar uses is determined by inference based on lighting data and the tv, radio, and mobile phone ownership.

Regression Analysis

To assess ownership of solar panel adoption and disadoption we use binary logistic multivariate regressions. The results produced are odds ratios which signal how each variable effects the odds of adoption as seen in equation 1 and 2.

Equation 1:

$$Y=\log(^{Pr(\text{solar panel ownership})/}{}_{Pr(\text{no ownership})})$$

Equation 2:

$$Y=\log(^{Pr(\text{disadoption})/}{}_{Pr(\text{solar panel ownership})})$$

Pooled Cross-Sectional Analysis

Equation 3:

$$Y_{ijk} = \beta_0 + \beta_1 x_{1i,t} + \beta_2 x_{2i,t} + \ldots + \boldsymbol{\mu} + \epsilon_{ijk}$$

Y_{ijkl} =Observed, $\boldsymbol{\mu}$= Fixed effects, ϵ_{ijk} = Random effects

For the pooled cross-sectional data, a multi level mixed logit method was used as the dataset contains several levels of data from district and region level. The estimating equation is given above where in the equation above Y= solar adoption, x=independent variables and $\boldsymbol{\mu}$= the fixed effects of the region. The data is analyzed as the data is clustered on the district and regional levels The independent variables are those listed below. Disadoption is not run in this model as the variable is only derived from the panel dataset.

Pure Panel Analysis

Equation 4:

$$y_{i,t} = \beta_0 + \beta_1 x_{1i,t} + \beta_2 x_{2i,t} + \ldots + + \varepsilon_{i,t}$$

The panel is analyzed using logit models (equation 2). In the equation below y= solar adoption, β= the coefficient, x= the independent variables, and t= time periods. The various independent variables used in the model are in the above section. The models for disadoption is only run with the aggregated variables due to a low sample size of those who disadopted.

Limitations of analysis

There are some limitations of the analysis. First, we do not have a clear picture of exactly what solar panel households are using and inferences are made based on asset ownership. Second, we rely on data regarding primary lighting source to link solar panel adoption with lighting services. The IHS does not include detailed data on use of solar technologies in households. Third, in creating the panel data focusing on household head, observations were cut from the dataset. This led to a smaller sample size which decreases the power of the regressions. This is especially true for the disadoption regression, where the sample size is so small that few variables are significant. Lastly, we assume that some of the differences in our results would not be effected by the differences that aroe from creating a true panel.

Results

Adoption and Disadoption of Solar Panel between 2010 and 2020

We examine adoption of solar panels using the full cross-sectional dataset of the IHS between 2010 and 2020. The first trend we look at is solar panel adoption.

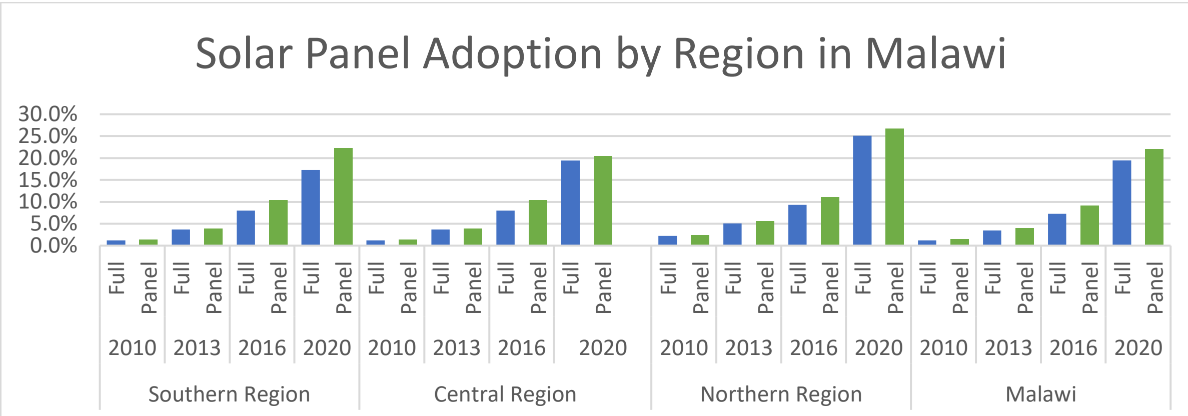

Figure 1. Graph of Solar Adoption and Disadoption in the Panel Dataset and Full Dataset from the IHS Dataset

Results show that solar panel ownership has increased in the country, Figure 1. Figure 1 shows solar panel ownership increasing across regions and the country from less than 1% in 2010 to around 20% in 2020. Largest gains in solar panel ownership is seen in the northern region where solar panel ownership is around 25% in 2020. Other regions also a rise in solar panel ownership but the lowest gains in adoption is around 20% in the southern region and lower than the average for the whole country.

The results in Table A2 show that solar panel adoption varies between urban and rural households too. 26.1% of rural households and 10.1% of urban households report owning a solar panel. In early waves, as seen in Table A2, solar ownership in rural and urban areas were less than a percent apart. However, as the growth of solar increased, rural households were adopting solar a lot more, as shown in the Table 2 were urban solar adoption in 2020 was at the same proportion as rural ownership in 2016, and urban adoption was 16 percentage points lower in than rural households.

As adoption grew, we also saw households in the panel data disadopt solar panels. A small dataset of 149 households disadopted solar panels starting in 2013 to 2010. These populations were more in urban areas than rural areas and also more in the northern region.

Descriptive Statistics of households that adopt solar panels

We explore the household characteristics associated with adoption of solar technologies using a series of panel regression models. The full set of descriptive statistics for the variables used in these models are found in Table A3 for the full IHS data and Tabel A4 for the panel dataset.

Household Head Characteristics

The household head variables examined were their age, gender, size of the household, and education. The key findings in the characteristic of the household reltates relate to the gender of the household head. In the adoption group, a small number of households that adopt are headed by females. Only 8.6% of the households are headed by females which is less compared to the whole study population that sees female headed households represent 16% of all households.

Indicators of wealth

There are two main indicators of wealth we look at, housing characteristics and asset ownership, as there is no income data in the survey. The housing characteristic variables examined are whether or not a house has iron sheets, brick walls, cement, or access to the grid as well as if the house is rented and if the house is in a rural area. For the physical structure of the house, adopting households have better quality houses compared to the whole population. In 2010 47% of houses had iron sheets for adopters while only 42% of the whole population had iron sheets. By 2020, nearly 70% of the adopters had iron sheets compared to 64% of the households in the whole population. Brick walls and cement floors follow a similar trend of increasing over time and adopters having higher percentage than the percentage for the whole sample. A major trend too is that adopters have a much higher access to the grid than the whole population. 2.4% of the whole population has grid access in 2010 and increases to 7.7% in 2020. However, in 2010, 12.4 % of adopting households have access to the grid and by 2020 the number increases to almost a quarter of households are connected to the grid.

The asset ownership variables are those assets that the literature suggest are related to solar use and are mobile phone, tv, or radio ownership. Mobile phone ownership sees a quick increase for adopters where 59% of houses had at least one mobile phone in 2010 and 81.7% of houses owned at least one mobile phone in 2020. For tv ownership, the percentage of households that owned a tv was less for adopters than the whole dataset and was true across all waves. Conversely, a greater percentage of adopters owned radios compared to the whole population and this holds true across all waves. Combining tv and radios, which is done as they both serve as forms of entertainment and sources of information, the percent of houses that own at least one of these items is higher for adopters than the whole population.

Geographic distribution of adopting households

Interestingly too, the adopting houses are more rural than the whole dataset and the key findings relate to the rural and urban divide. Approximately 80% of the adopters are in rural areas, a number ten percentage points higher than the whole population. Further a majority of the households are in rural areas which is because the majority of people in Malawi live in rural areas.

Main difference of Adopters and nonadopters:

There are also key differences between adopting households non adopting households. Nearly 20% of the non adopting households are headed by a female which is ove twice as high as adopting households where 8% of those households are female. Non- adopters, as seen in figure 3, also own less assets and worst quality houses which indicate a lower income status. A higher percentage of non adopter rent and are less rural compared to adopting households. Finally a smaller percentage of non adopter households (11.11% in 2020) are connected to the grid than adopting households (24% in 2020).

Descriptive Statistics of Households that Disadopt Solar Panels

Household head characteristics

The household head characteristics look at age, gender, and education. The key variable of disadopters is also the gender of the household head where the head is predominantly male headed, but one percentage point lower than that of the adopting houses.

Indicators of Wealth

The variables that looked at housing characteristics were, whether the house had iron sheets, brick walls, cement, access to the grid, if the house was rented, and if the house was in a rural area. Overall, housing quality improved throughout the study. The houses that had iron sheets rose from 60% in 2010 to 81% in 2020. The percentage of houses with iron sheets was also higher for the disadopters than the adopters in all waves. Houses with brick walls increased from 56% to 72% nearly matching the rise of the adopting houses saw. Cement flooring is the only variable that decreased over time, where 56% of houses had cement flooring in 2010 while 52% of the cement flooring in 2020, which is still higher than the adopting households.

The assets looked at for disadopters are the same as adopters and are tv, radio, and mobile phone ownership. TV ownership increased over the years going from 25% of the households in 2010 to 29% in 2020. The percentage of disadopters who had TVs was also 10% points higher than the percentage of adopters who had TVs. Radio ownership followed the similar trend as adopters where the percentage of radios owned decrease across the four waves. The percentage of radio ownership was 63% in 2010, nearly identical to the percentage of adopters, but fell much more to 36% of the households owned a radio by 2020. By 2020, the percentage of households who owned a radio was ten percentage points lower than the adopter households. For mobile phone ownership, 70% of the disadopting households had phones and was more than ten percentage points higher than adopting households in 2010. The percentage of households that owned a mobile phone in 2020, increased to 80% a number just one percentage point lower than adopting households.

Georgraphical trends of disadoption

For rural households, there is quite a disparity between the adopters and disadopters. The disadopter households are still mainly rural. However, only 67% of the households are rural for the disadopters, a number approximately sixteen percentage points lower than the adopting houses and approximately five percentage points lower than the whole dataset making the disadopters more urban than the adopters.

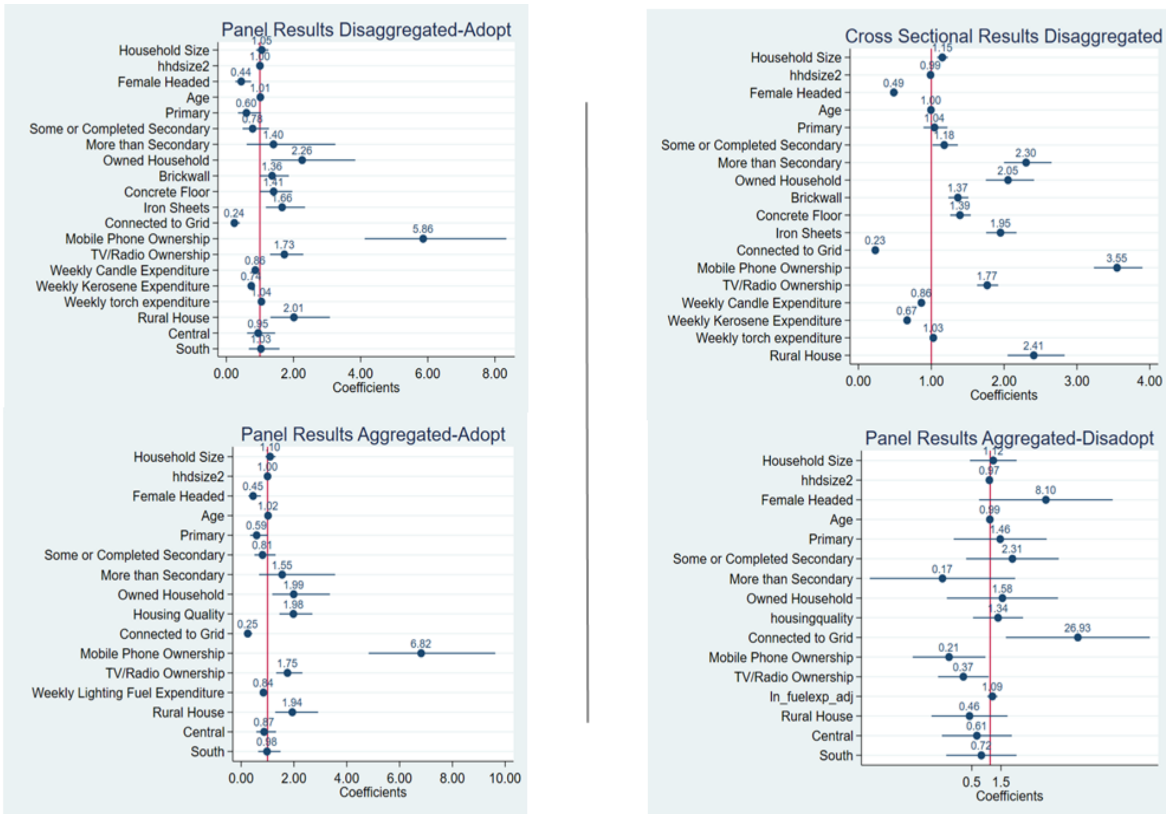

Figure 2. Coefficient Plots for regression models presented as odds ratios, the blue bars represent confidence interval, any bar that does not cross the red line is statistically significant to a 95% confidence level.

Household level determinants of adoption

In the top two panels and bottom right panels show regression results for adoption in coefficient plots, figure 2. The main findings are the impact of asset ownership, household gender, and rural/urban homes have on solar adoption, with the same directionality and statistical significance in both the panel dataset and cross sectional dataset. Female headed households saw a 56% decrease in the odds of adopting a solar panel. On the other hand, a household that owned a mobile phone increased the odds of adopting a solar panel by 682%. Owning a TV or radio also impacted solar ownership where owning a either made a house increased a households odss of owning a solar panel by 70%. Being in a rural area also positively impacted ownership, increasing the odds of solar panel ownership by 310%.

Household level determinants of disadoption

The bottom right panel in Figure 2 shows the coefficient plot for the regression results for disadoption of solar panels. Interestingly, having a connection to grid increased the odds of disadopting by 260%. Owning a TV or radio or a mobile phone was statistically significant to a 95% confidence level of decreasing the chance the that these household disadopted solar panels. The odds of disadopting decreased by 79% if the household owned a mobile phone and by 63% if the household owned a tv or radio. Following literature, two of the three primary reasons to own a solar panel is for tv/radio use or mobile phone charging, this result seems to support this hypothesis as if the household was using the panel to charge or power these assets then they may be less likely to get rid of the panel. While no other significance can be reported, it is important to note that the odds ratios switch between the adoption models and disadoption models for which points that households who disadopted are the ones that were already unlikely to adopt.

Solar Panel Usage

Given significant take up of solar technologies by households in Malawi, we then consider the services provided by solar technologies. Our expectation is that households adopting solar technologies are using them primarily for lighting, Figure 2 shows the three primary lighting source across Malawi comparing households that do not own or do own solar panels, the figure for the panel dataset is in Appendix Figure A1. The trend that is seen primary lighting sources in Malawi is that kerosene as a source decreases over the last decade while battery torches increase as a primary source. Other sources, which includes solar remains stagnant. Solar as a primary lighting source stays around 1% across the last decade and does not make an impact as a primary lighting source.

There difference between urban and rual lighting sources is also stark. Nearly half of urban households rely on electricity for lighting and the rest being made up by battery torch (36%), candles (13%), or other sources (~2%). Rural households though rely dominantly on battery torches that make up 86% of household's primary lighting. But still, solar as a lighting source is very low and in 2020, solar was the main source of lighting for of 0.67% of main lighting for urban houses and 1.47% of rural households.

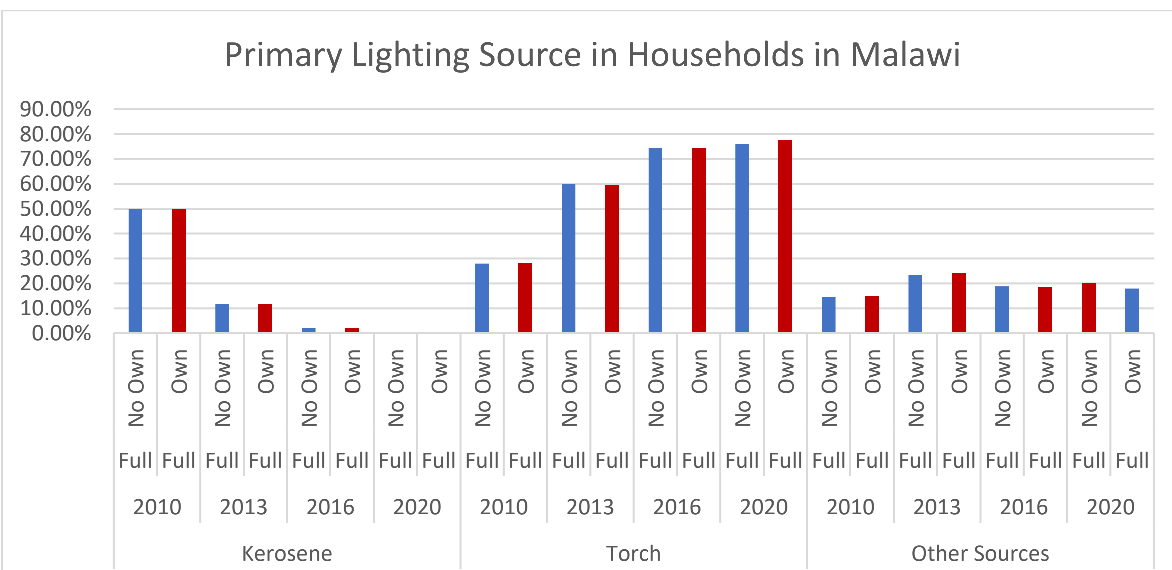

Figure 3. Primary Lighting Source for main lighting sources in Malawi

After looking at solar as a primary lighting source, we hypothesize that households use solar panels as a backup to grid electricity. Both the full and the panel datasets were restricted to only houses that have grid access and blackout lightingsources were generated (Table A2). Still, there appears to be no lighting story from solar sources. Among all the samples, solar as a backup energy source for grid electricity actually decreased throughout the panel. By far the largest change from 2016 to 2019 was the increased use of battery torches as a backup source during blackouts.

Given our finding that there is limited use of solar panels as a primary lighting source we then consider what other uses it might have in the household. Unfortunately the IHS data does not have information on energy services. Figure 3 shows potential uses of solar of those who own a solar panel in each wave for Malawi, panel dataset can be seen in Figure A2. Interestingly enough, mobile phone ownership, tv ownership, and radio ownership all decrease by 2020. Still, a high percentage of adopting households owned at least one of these assets compared to non adopters. compared these numbers to the non adopters in each wave with a two sample t-test. The ownership of assets was significantly higher for each category in each year as seen in the below figure. This could be evidence that more people are using solar panels for charging phones or powering tvs or radios than to provide lighting to their house, especially when including the fact that households that own these assets are more likely to own a solar panel and less likely to disadopt a panel.

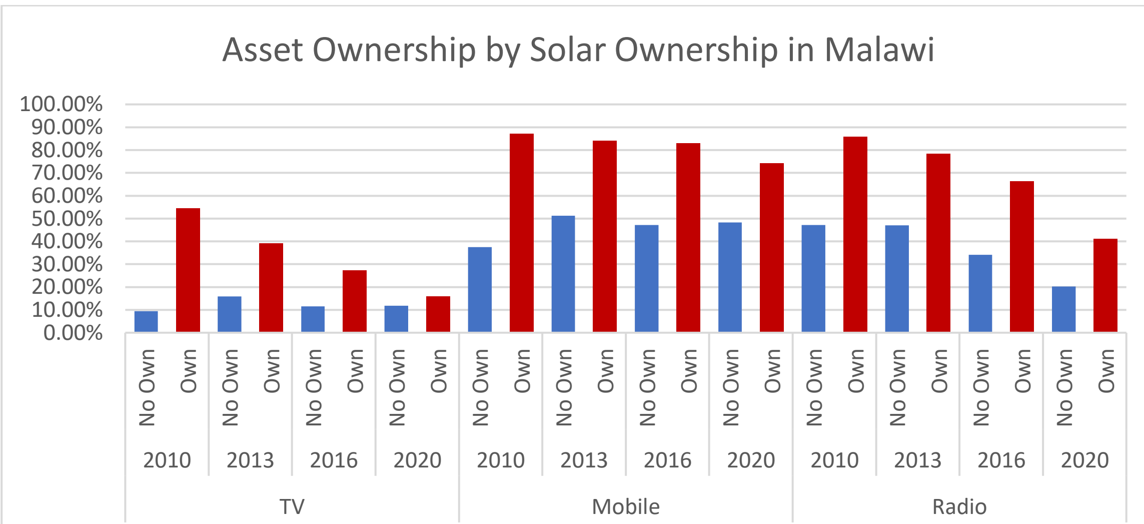

Figure 4. TV, Mobile, and Radio Ownership in Malawi for Households that do vs do not own solar

Section 5. Discussion

Malawi has seen a big increase in solar panel adoption. The increase in adoption could be due to the promotion efforts of the Malawi Rural Electrification Authority which has promoted solar in rural areas over the last decade and Malawi's commitment to the Energy Compact and promoting solar to achieve SDG 7. Further there is a robust number of solar firms, mostly having PAYGO business models, that help reduce financial barriers, identified in Girardeau et al 2021, to solar adoption that.

However while we can measure solar panel uptake, the benefits from solar panel use is hard to deduce. Access to lighting has a lot of key benefits (Esper et al 2013 and Wallach et al 2021). However, it does not appear that owning a solar panel in Malawi provides the benefits of lighting as rapid uptake of solar panels is not associated with increases of solar as a primary lighting source.

Instead due to the regression results and descriptive statistics, people appear to be using solar panels for TV's and Radios or Mobile Phones. These still provide essential services for livelihoods as mobile phones are key sources for communications and TV's/Radio's are sources of both information and entertainment. These other uses are also seen as substitute for solar energy use as well as lighting and people may prefer phones, tvs, or radios than lighting. This is not necessarily a negative as access to a radio has been shown to help household improve response to disasters. Such as households in Southern Malawi that had access to radios were more better prepared for Cyclone Idai in 2019 than households that did not have this source of information (Jagger in review). Still we are not certain what people actually use solar panels for and more research needs to be done. Further research can help policy makers better understand how people use solar panels in the household which can inform programs and projects in order to better promote solar and increase the goal of reaching SDG 7.

Gender

A concerning result of this study is that female headed households are less likely to adopt solar. This could have troubling consequences as access to clean energy is sometimes associated with reinforcing power dynamics in a household (Mensah and McWilson 2021). Such as male household headed may the decision making authority for the use of solar, whether it is for lighting, mobile phone charging, or tv/radios. While access to these technologies can increase equity, it only happens if the placement of the technology is in usable location (Mensah and McWilson 2021). If solar powered technologies are not always placed in the best location, such as the light being placed in the den instead of the kitchen, the radio being with the male, and the solar system charging the only phone in the house which belongs to the head, power structures could be reinforced in the household. In order to ensure a more equitable transition, programs should promote solar panels for female headed households.

It is important to acknowledge some bias in our results regarding gender. In creating the panel dataset, the proportion of households that were headed by males increased and were more than than the full dataset. This resulted in our regression models showing a large negative impact gender had on adopting solar panels. Sill though, when running the cross sectional regression with the full dataset, the same directional impact of household head gender was found for the whole dataset. Thus the magnitude of the panel regression may be bias but the directionality is not and female headed households are less likely to adopt solar.

Poverty/wealth status

Another interesting result in the study is that households that do adopt solar typically are more wealthy. This is shown in asset ownership and housing conditions which can indicate a household's wealth when household income data is unavailable (Filmer and Pritchet 2001, McKenzie 2005, and Smits and Steendijk 2014). The fact that households that adopt are wealthier can point to financial barriers to adopting solar. Subsidizing solar panels and promoting PAYGO systems could lead to more access to solar panels for a larger group of the population. Policies like these can help ensure poorer households are not left behind. This is especially important as poorer household face more burdens related to energy poverty such as health burdens from unhealthy fuels (Jessel et al 2019).

Location (Rural/Region)

Households that adopt solar tend to be rural and in the north region. This information is important as solar power ownership can reduce the energy gap in Malawi. Rural areas in Malawi are less electrified than urban areas and solar panels can offer a better source of electricity. Still the urban areas should not be ignored in promoting solar adoption. Going back to use, it is not unheard of that people will have different uses of solar in rural areas compared to urban areas. More research should be done on these populations and solar use to better understand how these populations use solar. This information can help policy makers better promote solar technologies across throughout the country.

By region, highest percentage of solar adoption is in the northern region. Policy makers should try to emphasize the central and southern regions to promote adoption. These two regions are more populated than the northern region and in turn can have more of a significant impact on promoting solar.

Disadoption

This study builds on the small amount of work done on disadoption. Due to the small sample size though, few significant variables are seen. The main influence to disadoption is that owning a phone or tv/radio leads to a decrease chance in disadopting which points more to the use of the solar panel. Going back to Alpizar et al's theoretical model of disadoption, these variables also follow their mode. As urban households were more likely to disadopt, this could reflect customers taste. Are data point to this has access to grid increases the odds of disadoption, which could mean households prefer to have grid access to solar when available. Further using a phone or tv/radio reflects the consumers taste again as the household enjoys using solar because they give them access to charging devices especially in rural areas. However, there is a lot more work on disadoption that needs to be done. More research is needed for why and who disadopts solar technologies and what do these people do instead. A better understanding of disadoption will help policy maker adjust programs and projects to minimize disadoption of solar and create more sustained use. This will help ensure Malawi reaches SDG 7.

Section 6. Conclusion

We find that several factors are associated with solar panel ownership including owning technologies requiring electricity (e.g., mobile phones and radios), owning your home (vs. renting), having higher quality housing, and having a residence in a rural area. Having access to grid electricity and having a female headed households are associated with being less likely to adopt solar panels. We do not find evidence that households are using solar technologies as a primary source of lighting.

These results are important for policy makers. The fact that rapid solar uptake is not correlated with an increase in solar lighting should encourage policy makers to reevaluate solar promotional programming to ensure that programs create the benefits policy makers want. The study also shows that rural people are more inclined to adopt solar and therefore to increase solar uptake, policy makers should work to reducing barriers such as financing and market access to increase energy access in these areas. Lastly, policy makers should also target female headed households to ensure they are not left behind in the dark.

Our analysis has some limitations. First, the IHS data does not have accurate data on solar panel use and all of our findings are based on inferences. Second, while we look at disadoption, the sample of disadopters is too low draw many conclusions. Third, the research is limited by its definition of adoption. We define adoption by owning a panel and we do not know if every household that owns a solar panel uses it, some of these households could be disadopters. More research needs to be done to better understand how people use solar panels which can help target populations to adopt them. Also more research should be done on disadoption, who disadopts and why. This could give a clearer definition between adoption and disadoption and we can better understand the nuances in using technology. Such as it is possible in our study that some adopters were actually disadopters but still owned their solar panel and this could have influenced our results.

Solar and renewable energy sources are key to achieving SDG 7. As is shown in this study, measuring access by assessing who owns ed solar technologies is not enough. How people use technologies is more nuanced than some expect as people do not always use technologies the way policy makers think they do.

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Appendix

Table A1: List of Companies Promoting Solar Products for Household Use, 2022

Company	**Location/ Big Projects**	**Products**	**Business Model**	**PAYGO System (if applicable)**	**PAYGO (YES/NO)**	**Website**
Vitalite	Malawi and Zambia	Solar Home Systems Cookstoves Solar Pumps	Pay As You Go- Daily, Weekly, and Monthly Payment Plans	$75 for whole system	Yes	http://www.vitalitegroup.com/
Yellow	Based out of Lilongwe	SHS	Retail cash and credit		Yes	https://www.yellow.africa/
Sunny Money	Focus on Kasungu	Solar Lights Solar Fan Brands: Sun King, pico solar, and ov multilight OV	Retail, wholesale, and pay as you go	Products range from 5,000-45,000 MWK	Yes	https://sunnymoney.org/

Zuwa Energy		Zuwa Brand SHS Kwacha 4 4 lights Rechargeable torch and radio Phone Charging Kwacha 6 6 lights Rechargeable torch and radio Phone Charging Macheza 4 lights 24" HD TV Phone Charging	Retail cash and credit and PAYG	Kwacha 4Kwacha 4 • Upfront- MWK 210,000 • 20 Month PAYG- 40,000 deposit, 8,500 Monthly Kwacha 6 • Upfront- 230,000 MWK • PAYG 20 Months- 46,000 deposit, 9,200 monthly Macheza (• Upfront- 600,000 MWK, • PAYG 20 Months- 120,000 Deposit, 24,000 monthly	Yes	https://zuwaenergymw.com

Solar Works	Malawi and Mozambique	Solar Family SW80 Special- 80 W battery, Charge phones, 12W Panel, Torch SW80 Lite- 80 W Battery, 12W, Phone Charging Solar Life SW80+TV 35 W Panel 24"TV, Radio, Ability to Charge phone, torch, 4 lights 80 W Battery SW155+TV 4 lights, 55W Pannel, 155W	PAYG through Airtel money or TNM Mpamba	Solar Family SW80 Special · Upfront MWK 155,000 · Pay As You go 30 Months, 10,000MK down payment, 7000 Monthly payment SW80 Lite · Upfront 165,000 MWK · Pay as you go 30 months, 12,000 down payment and 8,000 monthly · Pay as You go 18 months, 12,000 down payment, 11,000 monthly payment Solar Life SW80+TV · Upfront 410,000 MWK	Yes	https://www.solar-works.mw

		Hourse Batery, 24”TV, Torch, Phone Charging SW155+32TV 4 lights, 55 W panel, 155W Hours Battery, radio, TV, torch, phone charging		· 30 Months- 40,000 down payment, 20,000 monthly · 18 months- 40,000 down payment, 27,000 monthly SW155 +TV · Upfront 475,000 MWK · 30 Motnhs- 50,000 down payment 23,000 monthly · 18 months- 50,000 down payment, 30,000 monthly SW155 +32 TV · Upfront 550,000 MWK · 30months- 60,000 Down payment 36,000 monthly 18 Months- 60,000 down		

				payment, 29,000 monthly		

Sen Solar Engineering		Solar Pumps Solar Home Systems Victron Energy Quattro	Unavailable		No	https://sen-solar-engineering.business.site/#summary
Sonlite Solar	Projects:	Solar Home Systems: Brands: · Victron Energy · Canadian Solar · Pylontech · Orentz · Arco · Grundfos	By requesting a quote only		No	https://www.sonlitesolar.net/
Recapo	Lilongwe and Blantyre	2.5 W household systems Brand: · IndiGo	Weekly Pay as You go model	No info on amount per weekly payments · One time installation fee · Household owns unit after 80 activation payments (~80weeks of paying)	Yes	http://www.recaposolar.com/home.html

Sky Energy	Based in Blantyre Major Projects: · Mulanje Mission Hospital · Blantyre Residential Hybrid System	Solar Home Systems · Victron Energy · PylonTech · Acme · Fronius · SMA Solar Pumps Solar Water Heaters	Not Available on Website		No	http://www.skyenergyafrica.com/?fbclid=IwAR33y7vIRL9mYg7PnG3-Wr3oZNFiSAAr9MbirehIp5iDL5EVnPsOTXfWDXg
Danforth Solar	Based in Cape Maclear	Solar Water Pumps Only · Victron Energy · Lorentz	Not Available		No	http://danforthsolar.com/
Econo Power	Limbe	Solar Panels and Batteries	By quote only		No	https://econo-power.business.site/
Team Planet		15 W PICO solar that charge phones, powerbanks, and Torch Solar Box Kit 100W panel		Solar Box Kit		http://goteamplanet.com/

		and 60Ah battery				
Electricity for All		Two kiosks to provide electricity for 300 households At kiosks households can rent batteries			No	http://www.electricity4all.com/our-scope.html
Powered By Nature		Retail cash and Credit SHS Brand: Sun king Solar water heaters Solar Water pumps	SHS offer tv pack and laptop charging kit		No	https://www.poweredbynature-mw.com/
M-PAYG/x-solar	Malawi	Retail and PAYG Sun King and Biolite	PAYG through mobile money	No info about pricing structure in Malawi	Yes	

Green Impact Technologies		Retail and PAYG Brand Sun King and Biolite Solar Water pumps (PAYG) SAS Pv Sustems Solar Home Systems Improved Charcoal Stoves LPG gas stoves	PAYG model with mobile money payments	No info on pricing structure in Malawi	Yes	https://www.greenimpacttech.org/

Kumudzi Kuwale		Pico, SHS, larger systems	Two retail outlets and ~20 rural charging stations where customers can rent, buy, and/or charge solar powered equipment		No	https://www.kumudzikuwale.com/index.html
Total Malawi	All over Malawi	Retail Brands: · Sun king pico · d.light · sundaya t lite	Sells through total filling stations		No	https://totalenergies.mw/
One Acre Fund	Zomba	Pico/SHS systems			yes	oneacrefund.org
Wala Ltd	lilongwe	Solar Water Pumps			no	https://walacleanenergy.com/

Ricotec	Lilongwe and Blantyre	Pico/SHS systems			no	https://gestetner.mw/about-ricotec/
Zasolar	lilongwe	Pico/SHS systems			no	http://www.zasolarmw.org/
greentech services	Lilongwe				no	https://greentechmalawi.tech.blog/
Green Energy Solutions	Blantyre				no	https://www.facebook.com/GreenEnergyMalawi/
Kuwala Energy	Lilongwe	Pico/SHS systems		sunking roducts	no	kuwalaenergy.com

Table A2. Solar Panel Ownership in Malawi Urban vs Rural

	Full sample	Pure panel	Full sample	Pure panel
Year	Urban (%)	Urban (%)	Rural (%)	Rural (%)
2010	0.62	0.69	1.33	1.79
2013*	3.06	3.16	3.63	4.37
2016	4.66	6.69	7.85	10.03
2020	9.79	10.7	21.65	26.1

*The 2013 round of the IHS included only panel households.

Table A3. Descriptive Statistics for Full Dataset Non-Adopters, Adopters, and Whole Country (standard errors are in paranthesise)

	Non-Adopters						Adopters						Malawi					
	W1	W2	W3	W4	Min	Max	W1	W2	W3	W4	Min	Max	W1	W2	W3	W4	Min	Max
Household size, number of people	4.6(0.2)	5.0(0.1)	4.28(0.02)	4.3(0.02)	1	22	5.4(0.2)	5.6(0.3)	5.0(0.1)	4.9(0.04)	1	22	4.6(0.02)	5.0(0.01)	4.3(0.02)	4.4(0.02)	1	22
Female headed hhd (c.f. male)	0.2(0.0)	0.2(0.01)	0.3(0)	0.3(0)	0	1	0.1(0.02)	0.1(0.04)	0.1(0.01)	0.1(0.01)	0	1	0.2(0)	0.2(0.01)	0.3(0)	0.3(0)	0	1
Age of Household head (years)	42.2(0.2)	41.9(0.4)	43.4(0.2)	43.3(0.2)	13	113	41.5(1.1)	42.8(1.7)	41.8(0.5)	42.5(0.3)	17	96	42.2(0.2)	42.0(0.4)	43.3(0.2)	43.1(0.2)	13	113
No Education	0.8(0)	0.7(0.01)	0.8(0)	0.7(0.0)	0	1	0.7(0.04)	0.6(0.1)	0.8(0.01)	0.7(0.01)	0	1	0.8(0.0)	0.7(0.01)	0.8(0.0)	0.7(0.0)	0	
Completed Primary(0/1)	0.1(0.0)	0.1(0.01)	0.1(0)	0.1(0)	0	1	0.1(0.03)	0.1(0.04)	0.1(0.01)	0.1(0.01)	0	1	0.1(0.0)	0.1(0.01)	0.1(0.0)	0.1(0.0)	0	1
Completed Secondary (0/1)	0.01	0.2(0.1)	0.1(0)	0.1(0)	0	1	0.1(0.03)	0.2(0.0)	0.1(0.0)	0.1(0.01)	0	1	0.1(0.0)	0.2(0.01)	0.1(0.0)	0.1(0.0)	0	1
Completed More than Secondary(0/1)	0.0(0)	0.0(0)	0(0)	0.1(0.0)	0	1	0.03(0.02)	0.1(0.04)	0.0(0.01)	0.1(0.01)	0	1	0.01(0.0)	0.0(0.0)	0.0(0.0)	0.1(0.0)	0	1
Own household (c.f. rent)	0.88(0.0)	0.8(0.01)	0.9(0)	0.8(0)	0	1	0.9(0.02)	0.9(0.04)	0.9(0.01)	0.9(0.01)	0	1	0.9(0)	0.8(0.01)	0.9(0)	0.86(0)	0	1
House has brick walls (0/1)	0.5(0.0)	0.52(0.01)	0.6(0)	0.6(0.01)	0	1	0.8(0.03)	0.7(0.06)	0.8(0.01)	0.7(0.01)	0	1	0.5(0)	0.5(0.01)	0.6(0)	0.6(0)	0	1
House has concrete floors (0/1)	0.3(0.0)	0.3(0.01)	0.3(0)	0.3(0)	0	1	0.6(0.04)	0.5(0.06)	0.4(0.02)	0.4(0.01)	0	1	0.3(0)	0.4(0.01)	0.3(0)	0.3(0)	0	1
House roof has iron sheets (0/1)	0.4(0.0)	0.5(0.01)	0.5(0)	0.5(0.01)	0	1	0.8(0.04)	0.7(0.1)	0.7(0.02)	0.6(0.01)	0	1	0.4(0)	0.5(0.01)	0.5(0)	0.6(0)	0	1
House has access to the grid (0/1)	0.1(0.0)	0.1(0.01)	0.1(0)	0.1(0)	0	1	0.04(0.02)	0.1(0.04)	0.1(0.01)	0.1(0)	0	1	0.1(0)	0.1(0.01)	0.1(0)	0.1(0)	0	1
House has a mobile phone (0/1)	0.4(0.0)	0.5(0.01)	0.5(0)	0.5(0.01)	0	1	0.9(0.03)	0.8(0.04)	0.8(0.01)	0.7(0.01)	0	1	0.4(0)	0.5(0.01)	0.5(0)	0.5(0)	0	1
House has a tv or radio (0/1)	0.5(0.0)	0.5(0.01)	0.4(0)	0.3(0)	0	1	1.0(0.02)	0.9(0.040	0.8(0.01)	0.5(0.01)	0	1	0.5(0)	0.5(0.01)	0.4(0)	0.3(0)	0	1
Logged weekly expenditure on candles (USD)	0.9(0.02)	1.4(0.1)	0.9(0.02)	0.7(0.02)	0	8.7	1.2(0.2)	1.3(0.3)	0.5(0.1)	0.3(0.03)	0	8.4	0.9(0.02)	1.4(0.1)	0.9(0.02)	0.6(0.02)	0	8.7
Logged weekly expenditure on paraffin (USD)	2.5(0.03)	0.7(0.04)	0.1(0.01)	0.02(0)	0	9.8	1.8(0.2)	0.3(0.2)	0.03(0.01)	0.02(0.01)	0	8.7	2.5(0.03)	0.7(0.04)	0.1(0.01)	0.02(0)	0	9.8
Logged weekly expenditure on battery torches (USD)	0.4(0.02)	0.5(0.04)	0.5(0.02)	0.6(0.02)	0	12	1.1(0.2)	0.6(0.3)	0.8(0.1)	0.8(0.1)	0	11.6	0.4(0.02)	0.5(0.04)	0.5(0.02)	0.7(0.02)	0	12
Rural household (c.f. urban)	0.8(0.0)	0.72 (0.01)	0.8(0)	0.8(0)	0	1	0.9(0.02)	0.8(0.1)	0.9(0.01)	0.9(0.01)	0	1	0.8(0)	0.7(0.01)	0.8(0)	0.8(0)	0	1
North	0.2(0)	0.1(0.01)	0.2(0.0)	0.2(0.0)	0	1	0.4(0.04)	0.2(0.04)	0.3(0.01)	0.3(0.01)	0	1	0.2(0.0)	0.1(0.01)	0.2(0.0)	0.2(0.0)	0	1
Central	0.3(0)	0.4(0.01)	0.3(0.0)	0.3(0.0)	0	1	0.4(0.04)	0.4(0.1)	0.4(0.02)	0.3(0.01)	0	1	0.3(0.0)	0.4(0.01)	0.3(0.0)	0.3(0.0)	0	1
Southern	0.5(0)	0.5(0.01)	0.5(0.0)	0.5(0.0)	0	1	0.3(0.04)	0.4(0.1)	0.4(0.02)	0.4(0.01)	0	1	0.5(0.0)	0.5(0.01)	0.5(0.0)	0.5(0.0)	0	1
N=	12123	1921	11542	9206	-	-	147	69	905	2228	-	-	12271	1990	12447	11434	-	-

Table A4. Descriptive Statistics for Panel Dataset Non Adopters, Adopters, Disadopters and Full Sample (standard errors are in paranthesise)

	Non-Adopters						Adopters						Disadopters						Panel					
	W1	W2	W3	W4	Min	Max	W1	W2	W3	W4	Min	Max	W1	W2	W3	W4	Min	Max	W1	W2	W3	W4	Min	Max
Household size, number of people	5.0 (0.1)	5.4 (0.1)	5.2 (0.1)	5.2 (0.1)	1	20	5.7 (0.7)	5.5 (0.4)	6.2 (0.3)	6(0.2)	1	20	-	6.3 (0.8)	4.2 (0.5)	6.1 (0.3)	2	12	5.0(0.1)	5.4(0.1)	5.3(0.1)	5.4(0.1)	1	20
Female headed hhd (c.f. male)	0.2(0.01)	0.2(0.01)	0.2(0.01)	0.2(0.01)	0	1	0.1 (0.1)	0.1(0.03)	0.1 (0.02)	0.1(0.02)	0	1	-	0.1(0.1)	0.1(0.1)	0.1(0.1)	0	1	0.2(0.01)	0.2(0.01)	0.2(0.01)	0.2(0.01)	0	1
Age of Household head (years)	41.8(0.45)	45.0(0.5)	48.1(0.5)	51.1(0.5)	16	95	41.8 (2.8)	44.2(2.08)	46.1(1.5)	49.9(0.9)	26	84	-	44.4(4.5)	45.7(2.8)	50.9(2.5)	29	84	41.8(0.5)	44.9(0.4)	47.9(0.4)	50.8(0.4)	16	95
No education(0/1)	0.8(0.01)	0.7(0.01)	0.8(0.01)	0.7(0.02)	0	1	0.93(0.1)	0.6(0.1)	0.8(0.04)	0.8(0.03)	0	1	-	0.4(0.2)	0.8(0.1)	0.6(0.1)	0	1	0.8(0.01)	0.7(0.01)	0.8(0.01)	0.7(0.01)	0	1
Completed Primary(0/1)	0.1(0.01)	0.1(0.01)	0.1(0.01)	0.1(0.01)	0	1	0.1(0.1)	0.1(0.1)	0.1(0.03)	0.1(0.01)	0	1	-	0.1(0.1)	0.1(0.1)	0.2(0.1)	0	1	0.1(0.01)	0.1(0.01)	0.1(0.01)	0.1(0.01)	0	1
Completed Secondary (0/1)	0.1(0.01)	0.2(0.0)	0.1(0.01)	0.1(0.01)	0	1	0(0.0)	0.2(0.1)	0.1(0.03)	0.1(0.02)	0	1	-	0.3(0.2)	0.2(0.1)	0.1(0.04)	0	1	0.1(0.01)	0.2(0.01)	0.1(0.01)	0.1(0.01)	0	1
Completed More than Secondary(0/1)	0.0(0)	0.0(0.0)	0.0(0.0)	0.1(0.01)	0	1	0(0.0)	0.1(0.04)	0.0(0.02)	0.0(0.01)	0	1	-	0.1(0.1)	0.1(0.1)	0(0.0)	0	1	0.0(0.0)	0.0(0.01)	0.0(0.0)	0.1(0.01)	0	1
Own household (c.f. rent)	0.8(0.01)	0.8(0.01)	0.9(0.01)	0.8(0.01)	0	1	0.9(0.1)	0.9(0.04)	0.9(0.03)	0.9(0.02)	0	1	-	1(0.0)	0.9(0.1)	0.9(0.04)	0	1	0.8(0.01)	0.8(0.01)	0.9(0.01)	0.9(0.01)	0	1
House has brick walls (0/1)	0.4(0.02)	0.6(0.02)	0.6(0.02)	0.6(0.02)	0	1	0.6 (0.1)	0.6(0.1)	0.8(0.04)	0.7(0.03)	0	1	-	0.9(0.1)	0.8(0.1)	0.8(0.8)	0	1	0.4(0.02)	0.6(0.02)	0.6(0.02)	0.7(0.01)	0	1
House has concrete floors (0/1)	0.3(0.01)	0.3(0.02)	0.4(0.02)	0.4(0.02)	0	1	0.5(0.1)	0.4(0.1)	0.4(0.1)	0.4(0.03)	0	1	-	0.4(0.2)	0.6(0.1)	0.5(0.1)	0	1	0.4(0.01)	0.4(0.01)	0.4(0.02)	0.4(0.02)	0	1
House roof has iron sheets (0/1)	0.4(0.02)	0.5(0.02)	0.6(0.02)	0.6(0.02)	0	1	0.7(0.1)	0.7(0.1)	0.7(0.1)	0.7(0.03)	0	1	-	0.8(0.2)	0.9(0.1)	0.8(0.1)	0	1	0.4(0.02)	0.5(0.02)	0.6(0.02)	0.6(0.02)	0	1
Combined variable on housing quality (cf house does not have iron sheets, brick house, and concrete floors) (0/1)	0.2(0.01)	0.2(0.01)	0.3(0.02)	0.2(0.02)	0	1	0.3(0.1)	0.3(0.1)	0.4(0.1)	0.3(0.03)	0	1	-	0.4(0.2)	0.5(0.1)	0.4(0.1)	0	1	0.2(0.01)	0.2(0.01)	0.3(0.01)	0.3(0.01)	0	1
House has access to the grid (0/1)	0.1(0.01)	0.1(0.01)	0.2(0.01)	0.2(0.02)	0	1	0.4(0.2)	0.2(0.2)	0.2(0.1)	0.1(0.03)	0	1	-	0(0.0)	0.2(0.10	0.3(0.1)	0	1	0.1(0.01)	0.2(0.01)	0.2(0.01)	0.2(0.01)	0	1
House has a mobile phone (0/1)	0.5(0.02)	0.5(0.02)	0.6(0.02)	0.6(0.02)	0	1	0.9(0.1)	0.8(0.6)	0.9(0.03)	0.8(0.03)	0	1	-	0.7(0.2)	0.8(0.1)	0.8(0.1)	0	1	0.5(0.02)	0.5(0.02)	0.6(0.020)	0.6(0.02)	0	1
House has a tv or radio (0/1)	0.6(0.02)	0.6(0.02)	0.5(0.02)	0.4(0.02)	0	1	0.9(0.1)	0.8(0.6)	0.8 (0.04)	0.6(0.03)	0	1	-	0.8(0.2)	0.7(0.1)	0.6(0.1)	0	1	0.6(0.02)	0.6(0.02)	0.5(0.02)	0.5(0.02)	0	1
Aggregated logged weekly expenditure	4.0(0.1)	2.2(0.1)	1.9(0.1)	1.2(0.1)	0	8.7	4.3(0.8)	1.8(0.5)	1.2(0.2)	0.8(0.12)	0	7.6	-	1.5(1.0)	2.4(0.7)	1.09(0.4)	0	7.1	4.0(0.1)	2.2(0.09)	1.8(0.1)	1.1(0.1)	0	8.7
Logged weekly expenditure on candles (USD)	1.2(0.1)	1.3(0.8)	1.3(0.1)	0.8(0.1)	0	8.7	1.3(0.7)	1.3(0.4)	0.7 (0.2)	0.3(0.1)	0	7.6	-	0.8(0.8)	1.6(0.6)	0.7(0.3)	0	7.1	1.2(0.1)	1.3(0.1)	1.3(0.1)	0.7(0.1)	0	8.7
Logged weekly expenditure on paraffin (USD)	2.9(0.1)	0.7(0.1)	0.1(0.03)	0.02(0.01)	0	8.5	3.0(0.9)	0.4(0.3)	0.1 (0.1)	0.02(0.02)	0	7.1	-	0.7(0.7)	0(0.0)	0.0(0.0)	0	6.1	2.9(0.1)	0.7(0.1)	0.1(0.03)	0.02(0.01)	0	8.5
Logged weekly expenditure on battery torches (USD)	0.2(0.03)	0.3(0.4)	0.5(0.1)	0.4(0.04)	0	7.6	1.5(0.7)	0.2(0.2)	0.5 (0.2)	0.5(0.1)	0	6.6	-	0(0.0)	0.8(0.4)	0.5(0.24)	0	5.9	0.3(0.03)	0.3(0.04)	0.5(0.04)	0.4(0.04)	0	6.4
Rural household (c.f. urban)	0.7(0.01)	0.7(0.01)	0.7(0.01)	0.7(0.02)	0	1	0.9 (0.1)	0.8(0.1)	0.8 (0.04)	0.9(0.02)	0	1	-	1.0(0.0)	0.7(0.1)	0.7	0	1	0.7(0.01)	0.7(0.01)	0.7(0.01)	0.7(0.01)	0	1
North	0.2(0.01)	0.2(0.01)	0.2(0.01)	0.2(0.01)	0	1	0.2(0.1)	0.2(0.1)	0.2(0.04)	0.2(0.02)	0	1	-	0.2(0.2)	0.2(0.1)	0.2(0.1)	0	1	0.1(0.01)	0.1(0.01)	0.1(0.01)	0.1(0.01)	0	1
Central	0.4(0.02)	0.4(0.02)	0.4(0.02)	0.4(0.02)	0	1	0.4(0.1)	0.4(0.1)	0.5(0.1)	0.4(0.03)	0	1	-	0.6(0.2)	0.3(0.1)	0.5(0.1)	0	1	0.4(0.02)	0.4(0.02)	0.4(0.02)	0.4(0.02)	0	1
Southern	0.4(0.02)	0.4(0.02)	0.4(0.02)	0.4(0.02)	0	1	0.4(0.1)	0.4(0.1)	0.4(0.1)	0.4(0.03)	0	1	-	0.22(0.2)	0.5(0.1)	0.3(0.1)	0	1	0.4(0.02)	0.4(0.02)	0.4(0.02)	0.4(0.2)	0	1
N=	1002	976	924	793	-	-	15	41	93	224	-	-	-	9	20	39	-	-	1017	1017	1017	1017	-	-

TABLE A5. Household-level determinants of adoption of solar technologies as odds ratios, standard errors are in paranthesis

	(1)	(2)	(3)	(4)
	Cross-Sectional Disaggregated	Panel Adopt Disaggregated	Panel Adopt Aggregated	Panel Disadopt Aggregated
Household size, number of people	1.152***	1.055	1.096	1.123
	(0.0377)	(0.0933)	(0.0969)	(0.503)
Household size squared	0.990***	1.001	0.999	0.972
	(0.00282)	(0.00619)	(0.00620)	(0.0358)
Female headed hhd (c.f. male)	0.485***	0.444***	0.453***	8.102
	(0.0277)	(0.115)	(0.116)	(10.38)
Age of Household head (years)	0.995***	1.013**	1.017***	0.988
	(0.00143)	(0.00577)	(0.00568)	(0.0169)
Education of Household Head (c.f. no education)				
Completed Primary	1.044	0.598*	0.586*	1.456
	(0.0837)	(0.167)	(0.162)	(1.297)
Completed Secondary	1.178**	0.783	0.810	2.305
	(0.0884)	(0.193)	(0.197)	(2.046)
Completed More than Secondary	2.302***	1.404	1.553	0.167
	(0.166)	(0.601)	(0.657)	(0.232)
Own household (c.f. rent)	2.054***	2.258***	1.990**	1.584
	(0.168)	(0.612)	(0.532)	(1.688)
Housing Characteristic				
House has brick walls (0/1)	1.366***	1.363*		
	(0.0699)	(0.217)		
House has concrete floors (0/1)	1.394***	1.408**		
	(0.0720)	(0.240)		

House roof has iron sheets (0/1)	1.950***		1.661***				
	(0.106)		(0.292)				
Combined variable on housing quality (cf house does not have iron sheets, brick house, and concrete floors) (0/1)					1.979***		1.343
					(0.313)		(0.644)
House has access to the grid (0/1)	0.232***		0.238***		0.248***		26.93**
	(0.0210)		(0.0636)		(0.0670)		(37.15)
House has a mobile phone (0/1)	3.550***		5.863***		6.817***		0.213**
	(0.170)		(1.054)		(1.200)		(0.149)
House has a tv or radio (0/1)	1.768***		1.728***		1.754***		0.365**
	(0.0739)		(0.249)		(0.250)		(0.177)
Aggregated logged weekly expenditure (USD)					0.844***		1.087
					(0.0223)		(0.105)
Logged weekly expenditure on candles (USD)	0.864***		0.863***				
	(0.0111)		(0.0313)				
Logged weekly expenditure on paraffin (USD)	0.668***		0.744***				
	(0.0154)		(0.0385)				
Logged weekly expenditure on battery torches (USD)	1.028***		1.045				
	(0.00908)		(0.0458)				
Rural household (c.f. urban)	2.407***		2.012***		1.938***		0.460
	(0.199)		(0.438)		(0.403)		(0.335)
Region (c.f. northern region)					0.871		0.607
Central Region			0.947		(0.185)		(0.407)

			(0.207)		0.979		0.718
Southern Region			1.030		(0.210)		(0.484)
			(0.226)				
Constant			0.00159***		0.00199***		
			(0.000937)		(0.00114)		
Observations	38,142		4,068		4,068		149
Number of pid			1,017		1,017		110
seEform in parentheses							

*p<0.10, **p<0.05, ***p<0.01

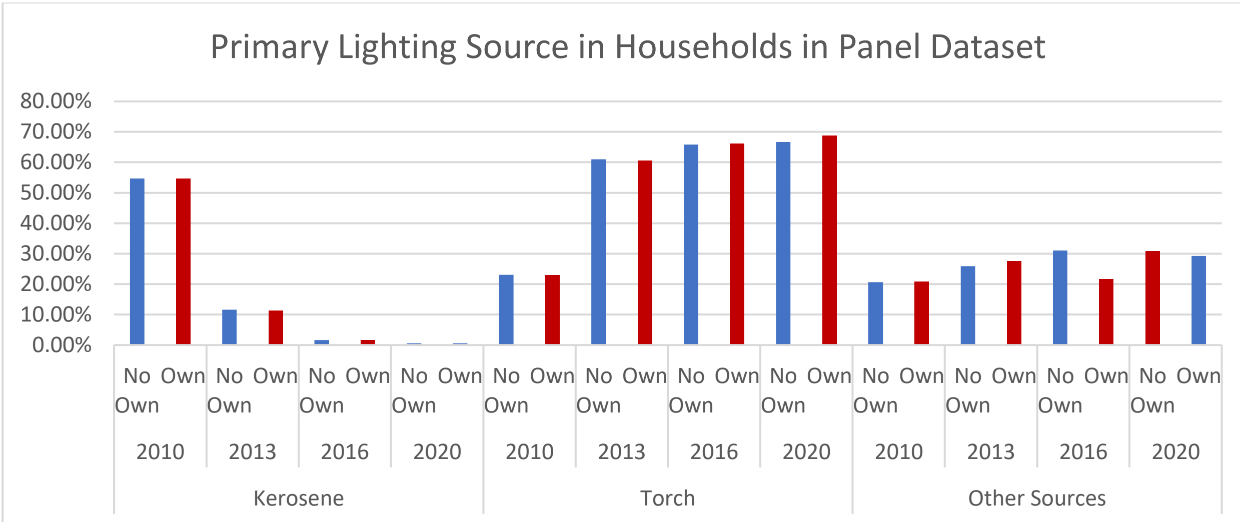

Figure A1. Three main primary lighting sources in households in the IHS Panel Dataset

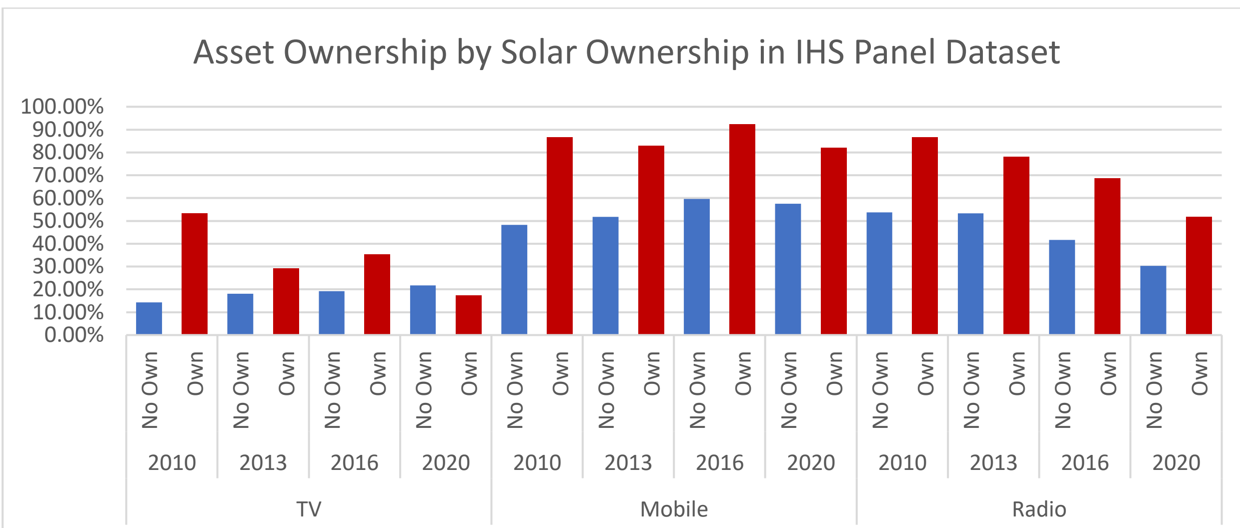

Figure A2. TV, Mobile Phone, and Radio ownership in IHS Panel Dataset