Does solar provide sustainable energy for all? Examining adoption and sustained use of household solar technologies in Malawi

by

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Abstract

Malawi is one of the poorest countries in the world, with one of the lowest rates of electricity access, particularly in its rural areas. However, the Government of Malawi aims to achieve universal electrification by 2030 through a variety of grid and off-grid strategies, including the promotion of decentralized solar technologies. Our study assesses the uptake and sustained use of solar home systems and standalone solar panels in rural areas of Malawi to explore the efficacy of household-level solar technologies in achieving universal energy access. We analyze survey data from 2,503 households as part of a two-period quasi-experimental quantitative impact evaluation to address three research questions: 1) what types and capacities of solar products do households use; 2) what factors are associated with the adoption of household-level solar technologies; and 3) as households adopt solar products, what factors affect whether they expand, maintain, or contract their supply of solar products over time? Through a series of linear and logit models, we find that the solar energy capacity of most solar devices and households is extremely low, highlighting the need for further research into the impacts of household-level solar technologies across differing capacity levels. Additionally, we identify several demographic and economic characteristics associated with household-level solar technology adoption and sustained use. Notably, our data suggest that low socioeconomic status is a major barrier to solar technology adoption, as well as to the maintenance or expansion of a household's supply of solar technologies over time. As such, we recommend targeted financial support for low-income households to ensure household-level solar technologies can be an effective electrification strategy in rural areas of Malawi.

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1. Introduction

As outlined in United Nations Sustainable Development Goals, providing universal electricity access is critical to improving the wellbeing of people around the world, including across economic, health, and education outcomes. Sustainable Development Goal 7 targets universal access to affordable, reliable, and modern energy services by 2030 (United Nations (UN), 2024). While energy access has increased substantially in recent years, the pace of electrification has remained relatively stagnant in Sub-Saharan Africa since 2010 (United Nations (UN), 2023). Recently, the Covid-19 pandemic caused a substantial slowdown in the rate of electrification due to its significant logistical and economic impacts (International Energy Agency (IEA), 2022). As of 2021, just 51% of people in Sub-Saharan Africa have access to electricity (World Bank, 2024).

The African continent faces several critical challenges in order to increase energy access. Rapid population growth and urbanization trends are projected to dramatically increase the demand for energy and threaten to outpace electrification efforts. Furthermore, nearly 700 million people in Sub-Saharan Africa, or 58%, live in rural areas, which are particularly hard to reach and costly to electrify through centralized grid expansion (International Energy Agency (IEA), 2022; World Bank, 2024). Where electricity is available, energy affordability continues to be a barrier to access. The upfront cost of electricity connection is oftentimes too expensive, particularly for low-income households and those living in poverty. In addition, regular electricity payments have shown to be overly burdensome for many grid-connected households. In 2021, 30% of people with an existing electricity connection could not afford even a basic bundle of electricity services (International Energy Agency (IEA), 2022). Moreover, even for those who are grid connected and pay for electricity services, the supply of electricity is highly unreliable in many parts of the continent, causing many firms and households to experience regular blackouts (International Energy Agency (IEA), 2022; Toman & Peters, 2017). To overcome these challenges and achieve universal electrification across the African continent by 2030, annual rates of electrification must triple current rates, and financial investments into the African energy sector must double (International Energy Agency (IEA), 2022).

African governments are drawing on both centralized grid and decentralized, off-grid solutions to increase energy access across the continent. Off-grid technologies, including mini grids and renewable energy systems like standalone solar panels and solar home systems, have gained particular traction as strategies for increasing electrification in rural areas (International Energy Agency (IEA), 2024). Africa has immense solar energy potential, with 60% of the world's best solar resources located within the continent, and most of it currently untapped (International Energy Agency (IEA), 2022). Moreover, the cost of smaller, off-grid technologies like solar home systems has dropped dramatically over the past decade, making these technologies increasingly viable, low-cost electrification strategies, particularly in Africa's rural areas (Toman & Peters, 2017). However, although decentralized solar technologies are becoming key tools for electrification in rural areas, some research suggests that they may not be enough to reach the poorest of households, and additional financial support may be required to achieve universal electricity access (International Energy Agency (IEA), 2022).

Our study focuses on Malawi, a small landlocked country in southeastern Africa. Malawi is one of the poorest countries in the world and has one of the lowest rates of electricity access (World Bank, 2023). In 2021, 14.2% of people in Malawi had access to electricity, with 54.2% access in urban locations, and just 5.6% in rural areas (World Bank, 2024). Electrification has been very slow in Malawi, although energy access in urban areas has been increasing faster than in rural areas. Over the past decade, the access to electricity increased by 21.6% in urban areas, but just 2.6% in rural areas (World Bank, 2024). In Malawi's 2018 National Energy Policy, the country identified energy as a priority sector in order to promote socioeconomic development within the country. The Government of Malawi has noted that access to electricity remains a major challenge in the country due to factors such as high costs of grid connection and inadequate capacity by the national power transmission and distribution company, Electricity Support Corporation of Malawi (ESCOM), to connect customers to the grid. The Government of Malawi has set universal energy access targets in line with Sustainable Development Goal 7 and is prioritizing rural electrification, especially for households, grain mills, and social service facilities. To accelerate rural electrification efforts, the Government is promoting grid and off-grid options, namely mini grid systems and solar panels. The Government is further supporting these endeavors by encouraging a private sector led energy supply industry, including promoting the manufacturing of standalone solar panels (Government of Malawi (GoM), 2018). While the Government of Malawi, as well as other Africa nation governments, are optimistic about the potential of decentralized solar technologies to accelerate progress towards universal electrification, results are largely mixed on whether solar is truly accessible for all.

This paper focuses on three questions to understand to what extent solar can promote universal electrification in Africa. We assess these research questions using household-level survey data from a two-period, quasi-experimental quantitative impact evaluation of household-level solar energy adoption and impact. Our first question focuses on what types of solar products households use in Malawi, including the range of product energy capacities and total household solar energy capacities. We seek to answer this question by examining the range of devices owned by each household across our sample. Furthermore, we explore the variety of energy capacities of solar devices owned in the sample, in Watts, as well as the variability in total household solar energy capacity, whereby we sum the Watts of all solar devices owned by each household. Second, we ask what factors are associated with the adoption of household-level solar technologies. We identify factors associated with ownership of two common types of solar devices, solar home system kits and standalone solar panels, at any point during our study to understand what types of households adopt solar technologies, and what conditions need to be met to spur adoption. We also utilize our two-period study design to identify factors associated with adoption of solar technologies between our two survey waves. Lastly, our third research question asks, as households adopt solar products, what factors affect whether they expand (adopt), maintain, or contract (dis-adopt) their supply, or stock, of solar products. We look across survey waves to determine whether households who owned solar products during our baseline survey adopted any new solar products, maintained the same number of solar products, or dis-adopted any solar products by endline. We then identify household characteristics associated with these different solar ownership evolutions.

2. Literature Review

2.1 Range of Household Solar Devices Being Adopted in Africa

Solar technology adoption in Africa has been widely studied, with several recent reviews summarizing the literature (Brunet et al., 2018; Kizilcec et al., 2022; Kizilcec & Parikh, 2020). However, a significant portion of studies have examined the uptake of solar home systems, with a very small number of studies on alternative solar technologies like solar lanterns or standalone solar panels. In a systematic review of household solar adoption, Girardeau et al. (2021) finds that 39 of 59 studies focused on solar home system, with just 3 papers each on solar lanterns and a mix of solar technologies (Girardeau et al., 2021). Another literature review of solar uptake authored by Lemaire (2018) also notes that the majority of articles analyzed were focused on solar home systems (61%), while few assessed solar lanterns (28%), and even fewer assessed a combination of solar devices (<10%). Several other literature reviews focus primarily on solar home system adoption in Africa, with little to no reference of alternative solar technologies (Kizilcec et al., 2022; Kizilcec & Parikh, 2020; Ojong, 2021).

In addition to the disproportionate focus on solar home systems in the literature, with little diversity in terms of types of solar technologies studied, there is very limited information in the literature on the range of solar energy capacities being adopted by households. However, the variation in energy capacities among household solar devices has been shown to be a critical component of solar adoption and use. Solar home systems can come in a wide range of energy capacities, from 11 Wp up to 300 Wp or higher (Kizilcec et al., 2022). Watkins (2016) notes the distinct differences in energy capacities among household solar products and classifies them into different tiers of energy access (Africa Progress Panel, 2017). Watkins (2016) also highlights that households with higher levels of income can afford larger sized solar products. Furthermore, the low capacity of many household solar products, namely solar home systems, has been identified as a deterrent of adoption and a barrier to households increasing their energy usage (Kizilcec & Parikh, 2020). While there is some evidence that the energy capacity of solar products impacts adoption and use patterns, Kizilcec and Parikh (2020) notes that just 11 out of 149 papers examined in the literature review discussed the energy generation capacity of solar products. There is a clear gap in the literature regarding analysis into the different energy generation capacities of solar products being adopted in Africa, as well as the prevalence of batteries and corresponding battery capacity.

2.2 Solar Adoption Determinants

There is a substantial literature on the topic of solar adoption in Africa, with numerous studies exploring the determinants of solar adoption in Africa. Several authors identified household characteristics associated with solar adoption. Lay et al. (2013) used national survey data to examine adoption patterns in Kenya (Lay et al., 2013). The authors found that income and education were positively correlated with solar home system adoption, as well cooking fuel choice. Bensch et al. (2015) conducted a quantitative evaluation in Burkina Faso and identified household expenditures, household size, and age of the household head to be correlated with adoption (Bensch et al., 2015). Mensah and McWilson (2021) also identified income and education as key determinants of household solar energy adoption in Ghana (Mensah & McWilson, 2021). However, although several studies have identified education level as a positive determinant of solar adoption, Smith and Urpelainen (2014) found no association between education level or rural location with solar adoption in Tanzania (Smith & Urpelainen, 2014). The literature review conducted by Kizilcec et al. (2022) highlighted the primary determinants of solar home system adoption as the reliability of alternative fuels, use of appliances that can be powered by a solar home system, including light bulbs, radios, chargers, and televisions, and higher income (Kizilcec et al., 2022). However, the review noted mixed findings on income as a determinant of adoption (Kizilcec et al., 2022). While Lay et al. (2013), Mensah and McWilson (2021), Smith and Urpelainen (2014), and Bensch et al. (2015) found income to be positively associated with adoption, Kennedy et al. (2019) found greater solar home system uptake among lower-income households in Rwanda and Kenya compared to higher-income households. However, the authors argue this is due to lower energy demand across low-income households, making solar home systems a more viable option in these communities (Kennedy et al., 2019). Similarly, the willingness to adopt a solar home system was also found to be higher in middle-class communities than in high-income communities in Tanzania. However, the authors attribute this dynamic to the occupancy status of the wealthier households, who tended to be renters rather than home owners (Akrofi et al., 2023). Mensah and McWilson (2021) also found housing tenure arrangements to be critical determinants of adoption (Mensah & McWilson, 2021). Findings on additional determinants of adoption in the literature include availability and awareness of solar home systems (Ondraczek, 2013), visibility and proximity, or clustering, of solar home systems (Kizilcec & Parikh, 2020; Lay et al., 2013), household size (Bensch et al., 2015; Kizilcec et al., 2022; Smith & Urpelainen, 2014), rural location (Kizilcec et al., 2022), gender of household head (Ojong, 2021), marriage status (Ojong, 2021), and performance expectation (Mensah & McWilson, 2021). Smith and Urpelainen (2014) also identified greater willingness to adopt solar home systems among electrified households in Tanzania compared to nonelectrified households, suggesting that solar may be used as a backup form of energy. Across the literature, affordability is among the most cited determinants of solar adoption (Kizilcec et al., 2022; Ondraczek, 2013). Kizilcec and Parikh (2020) find that pay-as-you-go (PAYG) models of solar home system provision seem to increase adoption, although PAYG models are dependent on mobile phone ownership and literacy (Kizilcec & Parikh, 2020). In Malawi, lack of electricity, personal interest (Ngonda et al., 2023), and word of mouth and copy-cat impulses (Samarakoon, 2020) were found as key drivers of adoption.

Across the literature, affordability of household solar devices, including acquisition and maintenance costs, was identified as one of the most salient barriers to household solar adoption (Girardeau et al., 2021; Ketlogetswe & Mothudi, 2009; Kizilcec & Parikh, 2020; Muchunku et al., 2018; Ulsrud et al., 2015; Wamukonya, 2007). Grimm et al. (2017) assessed willingness to pay for solar kits in a randomized controlled trial in rural Rwanda. Although the study found households were willing to pay a substantial part of their expenditures for a solar kit, the willingness to pay was still well below actual market prices (Grimm et al., 2017). Even with PAYG financing options, household solar products continue to be unaffordable for many low-income households (Kizilcec & Parikh, 2020; Muchunku et al., 2018; Ojong, 2021). In addition, while the low-capacity of solar home systems has been cited as a motivating factor for adoption, the low capacity of these systems has also been cited as an adoption deterrent (Kizilcec et al., 2022). Similarly, Wamukonya (2007) found that the quality of solar home systems and the need for technical support for installation and maintenance over time deters households from adopting solar products (Wamukonya, 2007). In addition, Bensch et al. (2018) found that neither promotion programs nor branded solar products, compared to unbranded products, were effective at increasing adoption rates in Burkina Faso. Migration (Ketlogetswe & Mothudi, 2009), limited markets (Wamukonya, 2007), and inadequate knowledge (Kizilcec & Parikh, 2020) were also identified in the literature as barriers to adoption. While factors contributing to and deterring household solar adoption have been examined in several different studies, the research on this topic remains limited, especially in contexts with ultra poor households, and it remains geographically clustered.

2.3 Household Solar Device Build-Out over Time

While many studies focus on the determinants and barriers to solar adoption, once households do adopt solar products, the factors contributing to household build out, maintenance, or contraction of their collection of solar devices over time remains largely unstudied (Kizilcec & Parikh, 2020; Ojong, 2021). Modularity has been highlighted as a major advantage of solar home systems as compared to grid connection, as components can be assembled together to achieve greater energy capacity and power additional appliances (Narayan et al., 2016; Wamukonya, 2007). In Malawi, Samarakoon (2020) found that tinkering, adding, and replacing components of solar home systems was common among households, findings that the assembly of a “satisfactory” solar home system was often a “costly, iterative process” (Samarakoon, 2020). However, while modularly is a feature largely unique to solar technologies, few studies have examined how households build, maintain, or contract their systems over time.

Dis-adoption patterns, the patterns by which households get rid of or stop using their solar technologies, have been moderately studied in the solar literature. It is widely noted that solar home systems are oftentimes repossessed when households are unable to make regular payments. Ketlogetswe & Mothudi (2009) report that, during a solar pilot project in Botswana, 37% of solar homes systems were repossessed within the project reporting period due to the inability of households to make their recurring payments, as well as due to household migration (Ketlogetswe & Mothudi, 2009). Even with pay as you go, often known as PAYG, financial payment mechanisms, some low-income households are unable to continue making payments over time and have their systems repossessed (Ojong, 2021).

Technical and maintenance issues have also been cited as key contributors to dis-adoption of solar devices (Girardeau et al., 2021; Wamukonya & Davis, 2001). Samarakoon (2020) found that, in Malawi, a lack of local experts left many systems unable to be repaired. Although solar adoption determinants have been studied in depth in several Africa contexts, there is limited research on whether households continue to build-out their stock of solar devices or dis-adopt products over the long-term.

2.4 Malawian Context

The number of publications related to household solar uptake in Africa has increased dramatically over the past two decades (Brunet et al., 2018; Kizilcec et al., 2022). However, literature reviews on the subject have identified a large geographical gap in publications, including a disproportionate number of publications in South Africa and Kenya (Brunet et al., 2018; Girardeau et al., 2021; Kizilcec et al., 2022; Kizilcec & Parikh, 2020; Ojong, 2021). Countries around the world with low electrification rates and slow grid encroachment, like Malawi, have been largely understudied (Girardeau et al., 2021; Kizilcec & Parikh, 2020). However, energy poor countries have critical motivations for solar technology expansion, making it even more important to conduct research in these areas. A few studies have examined the Malawian context, including Samarakoon (2020) which conducted a qualitative, ethnographic study of solar home system adoption in the north of Malawi (Samarakoon, 2020) and Ngonda et al. (2023) which also used qualitative methods to investigate solar adoption in rural Malawi (Ngonda et al., 2023). Ehimen et al. (2023) also reviewed the history of decentralized renewable energy systems in Malawi, finding that a lack of resources at both the community and government levels is inhibiting national electrification efforts (Ehimen et al., 2023). As is evident in the Malawi context, Kizilcec et al. (2022) note that there is a significant lack of quantitative studies published on this topic (Kizilcec et al., 2022).

2.5 Gaps Filled

This paper adds several key contributions to the existing literature on the topic of solar uptake in Africa. Our study focuses on Malawi, a country in which this topic has not been studied very substantially, yet has nationwide goals to promote off-grid household solar technologies as a strategy to achieve universal electrification. By examining the Malawi context, we glean insights into the role decentralized solar technologies can play in electrifying households where grid access is uncommon. In particular, we focus on rural areas of Malawi where grid access is both largely unavailable and very slow to roll-out, adding to our understanding of whether solar technologies can be effective electrification alternatives to grid connection. In addition, drawing upon two waves of quantitative household survey data, we add rigorous empirical evidence on solar device adoption and use patterns.

In addition, we add depth to the literature on the expansion of solar technology in Africa by looking across two types of solar devices, as well as examining variations in solar energy capacity. We study household ownership of two types of solar devices, solar home system kits and standalone solar panels, including households that own both types, recognizing that households often assemble a complex set of solar devices. We employ a broad set of household and village level characteristics to enhance our understanding of determinants of and barriers to solar technology adoption. Furthermore, we go beyond solar device type by exploring the range of energy capacities, in terms of Watts, associated with the solar devices owned by our sample of households. In addition to assessing variations in solar energy capacity at the solar device level, we assess variations in solar energy capacity at the household level to explore the total energy capacity households obtain through their solar devices and to identify factors associated with different levels of total household solar energy capacity.

We further contribute to the existing knowledge base by exploring how households engage with the modularity feature of solar technologies, which has been minimally studied. Using our two-period study design, we follow households who owned a solar device at baseline to understand how they expand (adopt), maintain, or contract (dis-adopt) components of their total stock of solar devices by endline. As such, we examine the evolution of solar ownership over time to add depth to our understanding of the long-term viability and potential of household solar technologies.

3. Methods

3.1 Study Design

The standalone solar device market in Malawi has been expanding rapidly in recent years. Between 2020 and 2021, the market nearly quadrupled in size. Several new companies have entered the market, costs of solar have fallen, new financial payment schemes have emerged to ease solar adoption, and USAID and World Bank funded development initiatives have provided grants to support standalone solar companies. Standalone solar companies in Malawi commonly employ agents to promote their products in remote areas and distribute solar products through school teachers, associations, petrol stations, bus companies, and last mile entrepreneurs (Africa Clean Energy Technical Assistance Facility et al., 2021). In 2022, our team conducted an inventory of standalone solar providers in Malawi. We identified 18 active standalone solar companies across the country (see full list in Table A1).

This study was conducted as part of a quasi-experimental quantitative impact evaluation of household-level solar energy adoption and impact led by the Energy Poverty PIRE in Southern Africa (EPPSA) research team in partnership with VITALITE, one of the major standalone solar companies in Malawi. VITALITE offers a variety of solar products including solar home systems, solar generators, and solar irrigation kits. Like most solar home system providers in Malawi, VITALITE uses agents to promote their products in rural villages. VITALITE offers customers the ability to pay the costs of their solar devices upfront, or customers can pay with PAYG financing, with payments every day, week, or month (VITALITE Malawi, 2024).

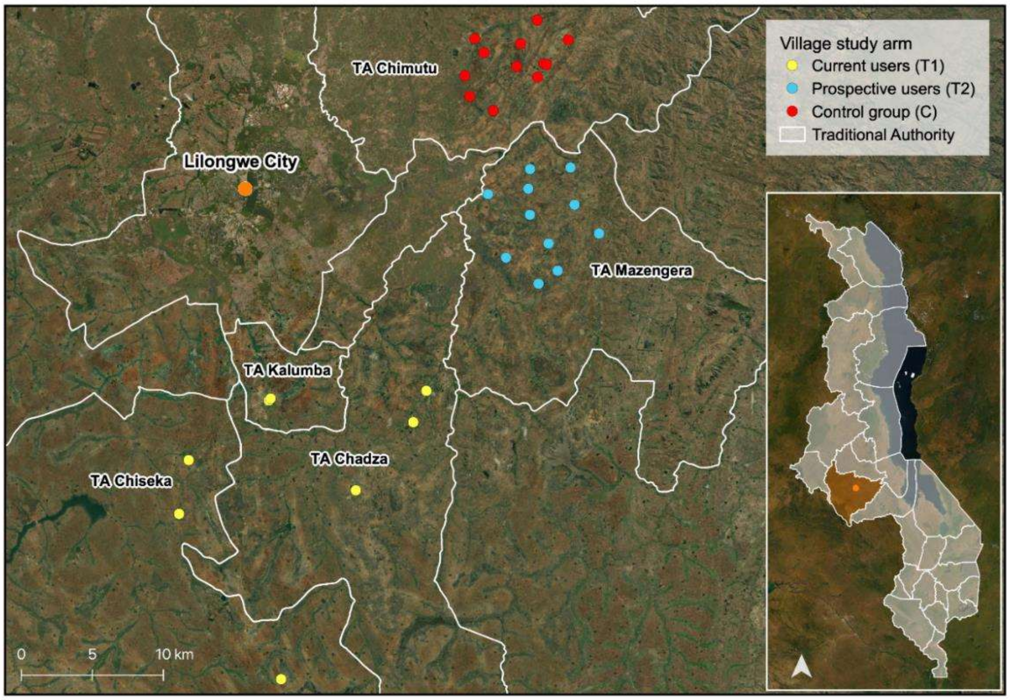
A baseline survey was conducted in July-August 2022, and a one-year follow-up survey was conducted 12 months later in July-August 2023. This study involved three arms: current users of VITALITE solar home systems (Treatment 1 or T1), prospective users of VITALITE solar home systems (Treatment 2 or T2), and a control group of non-owners of VITALITE solar home systems (Control or C).

We originally planned for the VITALITE team to target marketing efforts to prospective user (T2) villages between baseline and endline surveys and to avoid marketing directly in the control (C) group villages in an attempt to better understand determinants of adoption, as well as the impact of marketing on solar uptake. However, although VITALITE marketed to several T2 villages across our study area, due to unexpected weather and supply challenges, VITALITE was unable to promote in many of the T2 villages. As such, we modified our study design at endline to collect more data on solar home system users that could be used to assess adoption and impact. During endline data collection, we worked with village chiefs to identify households across all three study groups with purchased solar home system kits of any brand, not just VITALITE products, to add to our sample. Only such households residing within our predetermined study villages from baseline were added to the sample.

3.2 Study Area

This study was conducted in rural communities in the southeastern region of Lilongwe District in Malawi, outside of Lilongwe City. This area was selected due to the high concentration of solar home system firms operating in Lilongwe District. Surveys were conducted across five Traditional Authorities (TA) in the region: TA Chadza, TA Chiseka, and TA Kalumba (current users, T1); TA Mazengera (prospective users, T2); and TA Chimutu (control, C). Households were selected from a total of 28 villages: 7 villages in the T1 group, 11 villages in the T2 group, and 10 villages in the C group (see Appendix Table A2 for the study area characteristics of each study arm). Moreover, villages in our study area have a very low proportion of grid connected households (<2% of our sample was grid connected at baseline), giving us the ability to examine solar adoption trends for households with no other form of electricity. This also offers a more representative look at the broader population of rural Malawi, in which just 5.6% of households were grid connected in 2021 (World Bank, 2024).

Figure 1. Study area in Lilongwe District, Malawi



3.3 Sampling

At baseline, current user group households (T1) were selected from VITALITE's 2022 customer database. Current VITALITE customers located in the southeastern, rural Lilongwe District areas were contacted for interviews. Prospective user (T2) and control (C) group households were selected in a two-stage clustered sampling design. Several villages in each study arm were selected based on comparable population and geographic characteristics. Households were then randomly sampled from these villages.

To sample comparable villages, the study team carried out the following procedures. First, using a geographic information system, circles with a five-kilometer radius were overlaid on a map of Lilongwe District in several rural candidate areas where VITALITE had not implemented marketing efforts as of July 2022. Within the candidate areas, the following characteristics were compared: population density (based on gridded population data from WorldPop), Euclidean distance from Lilongwe City center, road distance and travel time based on Google Maps calculations from Lilongwe City center, whether or not high- and medium- voltage electric grid infrastructure ran through the center of the area, and estimated share of the population in the area that lived within one kilometer of electricity grid. Two areas were chosen in TA Mazengera and TA Chimutu based on similar characteristics (Appendix Table A2). Villages were then selected to represent full geographic coverage of the selected study areas and to represent the target number of households for the study. We randomly sampled households from ten communities for the control group arm and from eleven communities for the Treatment 2 arm by walking outward from the center of each village in all directions for complete geographic coverage. Every fifth household was selected for participation; if the household was not available or refused participation, the nearest household was selected for replacement.

3.4 Data Collection

Surveys were conducted over 6 weeks in July-August 2022, with follow-up surveys over 6 six weeks in July-August 2023. A team of 10 enumerators and 2 supervisors were recruited and trained in the weeks prior to each round of data collection at the Centre for Agricultural Research and Development (CARD) at the Lilongwe University of Agriculture and Natural Resources (LUANAR).

Enumerators conducted detailed household surveys taking approximately 45-60 minutes each at baseline, and slightly longer (60-90 minutes) at endline. Enumerators administered the questionnaires to the household head using a tablet to record their responses. The questionnaires contained 12 (baseline) and 15 (endline) modules, including questions about the household's demographics, economics, use of energy-consuming assets, detailed use of solar technologies, time-use, and hours of lighting (Table 1). Several modules and questions were added to the endline questionnaire, including an energy budgeting activity and a discrete choice experiment between different solar home system options. Additionally, at endline, questions covering topics including basic demographic information, non-energy related assets, and social capital were asked only to new households for whom we had not already collected this information.

Table 1. Survey modules

Survey Module		Wave
A	Household identification	Baseline and Endline
B	Household demographics and dwelling characteristics	Baseline and Endline
C	Land and livestock ownership	Baseline and Endline
D	Household assets	Baseline and Endline
E	Household energy sources	Baseline and Endline
F	Household fuel consumption for lighting	Baseline and Endline
G	Short recall of time-use during hours of lighting over past three days	Baseline and Endline
M	Energy budgeting	Endline only
O	Marketing implementation	Endline only
N	Discrete choice experiment	Endline only
H	Income from agriculture, livestock, and other sources	Baseline and Endline
I	Household expenditures	Baseline and Endline
J	Financial inclusion	Baseline and Endline
K	Social capital and trust/community cohesion	Baseline and Endline
L	Health service provision	Baseline and Endline

Enumerators were instructed to survey the exact same households at endline. However, 10% of baseline households (141 households) could not be reached at endline, primarily due to household migration. Enumerators were asked to attempt to reach the household several times by asking around in the village and/or by requesting a different enumerator to try finding the household. Only after several attempts, oftentimes over multiple days, could they receive approval from their supervisor to mark the household as an attritor. Throughout data collection, enumerators kept track of attrition and reasons why the household could not be reached.

Enumerators were instructed to interview the exact same respondent at endline that was interviewed at baseline. In the case that the baseline respondent was deceased, moved away, or was unable to be interviewed during the data collection period, enumerators could receive approval from their supervisor to interview a different respondent at endline. In instances where a different respondent needed to be interviewed at endline, enumerators recorded the reason for the different respondent and collected the new respondent's demographic information.

Additionally, since VITALITE was unable to market in T2 villages as planned between baseline and endline, we added 93 new households to the sample at endline. One to two days before the enumerator team arrived in each study village to conduct the surveys, supervisors were instructed to ask village leaders to a identify households in the village with purchased solar home system kits. We specified that the solar home systems did not need to have been purchased within the past 12 months, but they did need to have been purchased, not homemade. Adding these new households to the sample partially makes up for attrition and adds data on solar adoption and impact.

Overall, 1,279 households were interviewed at baseline, with 126 from the T1 group, 728 from the T2 group, and 425 from the C group. At endline, a total of 1,231 households were interviewed, including 138 from the T1 group, 686 from the T2 group, and 407 from the C group. Of those 1,231 households, 1,138 were panel households also interviewed at baseline (141 baseline households could not be reached at endline), 93 were new households added to the sample at endline. Overall, we completed 2,510 interviews (see Table 2). However, we drop 7 panel household endline observations from our sample during data analysis, as their income values were major outliers in the dataset. This drops our endline sample size to 1,224 households and our full sample size to 2,503.

Table 2. Household survey numbers across survey waves

Type of Household	Baseline	Endline	Total
Attritor Households	141	0	141
Panel Households	1,138	1,138	2,269
New Households	0	93	93
Full Sample	1,279	1,231	2,510

3.5 Data Analysis

3.5.1 Range of solar products and capacities

We first examine the range of types of solar technologies owned by households in our sample, as well as the corresponding energy capacities of the devices.

We look across our full sample of 2,503 households and calculate several proportions: 1) the proportion of households that owned at least one solar home system; 2) the proportion of households that owned at least one standalone solar panel; 3) the proportion of households that owned at least one of either device, and 4) the proportion of households that did not own either a solar home system or a standalone solar panel. Groups 1, 2, and 3 are not mutually exclusive, as households with a solar home system would be classified into groups 1 and 3, a household with a standalone solar panel would be classified into groups 2 and 3, and a household with a solar home system and a standalone solar panel would be classified into groups 1, 2, and 3. We calculate these proportions at baseline and endline, and disaggregate across our three study groups. In this study, we define a solar home system as a purchased kit including at least a solar panel, a control panel, light bulbs, and a battery. Larger solar home systems often include a radio or a television for an increased cost. In our analysis, we include solar home systems sold by VITALITE, as well as solar home systems sold by other providers in Malawi. In contrast, we define a standalone solar panel as a singular solar panel that a household did not purchase as part of a solar home system kit. Households with standalone solar panels often purchase batteries, light bulbs, and radios to which they connect their solar panel, creating a "self-made" solar home system. However, standalone solar panels are distinguishable from solar home systems in that the solar panels were not purchased as part of a kit.

We further explore the range and capacities of solar technologies owned by households in our sample by assessing the combination of solar home systems and standalone solar panels owned, as we found that households often own a mixture of the two types of technologies.

We then examine the distribution of energy capacities supported by solar technologies across our full sample. We compare the distribution of solar energy capacity across types of solar devices, namely 1) solar home systems; 2) small standalone solar panels; 3) medium standalone solar panels; and 4) large standalone solar panels to understand the variations in energy capacities between types and sizes of household-level solar technologies. Roughly in line with the Energy Sector Management Assistance Program's (ESMAP) Multi-Tier Framework (MTF) for measuring electricity access, we define small standalone solar panels as those with less than 5 Watts of energy capacity, medium standalone solar panels as those with 5-50 Watts of energy capacity, and large standalone solar panels as those with more than 50 Watts of energy capacity (Multi-Tier Framework, 2022). In our analysis, we categorize each individual solar technology owned across all households in our sample and examine the distribution between types of devices.

In addition to assessing per-device capacity, we explore the distribution of the total solar energy capacity possessed by each household in our sample. For every household, we sum the total solar energy capacity of each solar home system and/or standalone solar panel owned by the household and calculate a variable representing the household's total solar energy capacity, in Watts. We examine the distribution of total household solar energy capacity across three groups of households: 1) those with at least one solar home system; 2) those with at least one standalone solar panel; and 3) those with at least one of either a solar home system or a standalone solar panel.

3.5.2 Factors associated with household-level solar technologies

We explore individual and household level characteristics associated with ownership of our two focus types of solar technologies, solar home systems and standalone solar panels, through a variety of binary logit, generalized linear, and ordered logit models. We first compare several key household demographic characteristics across our three study groups to identify any significant differences. In particular, we seek to identify any significant differences between our Prospective User (T2) and Control (C) groups, which were constructed to be as comparable as possible. We look across all households in the full sample, including attritor households and new households added only at endline. For attritor and panel households, we examine the characteristics reported at baseline to avoid examining characteristics that may be influenced by new adoption of solar technologies between baseline and endline. For new household added at endline, we use demographic information reported at endline.

We then estimate a series of binary logit models to identify factors contributing to the ownership of each type of household solar technology. Our first set of binary logit models examines factors associated with solar technology ownership at baseline. We include all baseline observations, including both panel and attritor households. We also include new households added only at endline by backing out their solar ownership at baseline from their endline questionnaire responses. Specifically, we asked households at endline to report each solar device they currently owned and how long they had had the device. We therefore assumed that any devices at least 12 months old were also owned at baseline. We employ three logit models to identify factors associated with ownership of household level solar technologies. First, we construct a binary variable indicating whether households owned at least one solar home system at baseline (1=own, 0=do not own). Next, we construct another binary variable indicating whether households owned at least one standalone solar panel at baseline (1=own, 0=do not own). We then construct a third binary variable indicating whether households owned at least one solar home system or standalone solar panel at baseline (1=own, 0=do not own). These groups are not mutually exclusive; households that owned both types of devices would take on the value of 1 across all three variables. We run each of the three binary logit models independently using the same sample, clustering standard errors at the village level to account for differences across villages, and report the results of all three models as odds ratios in Table 5. We also run the same logit model with panel households only, where we do not include new households added only at baseline. Results from this panel household only model are presented in Table A3.

We use the following equation for our binary logit model:

$$P_r\left(Y_j = 1\middle|x\right) = \left[1 + e^{-(\beta_0 + \beta_1 Household\ characteristics + \beta_2 Individual\ characteristics + \varepsilon_j)}\right]^{-1}$$

We include a series of independent variables in the model covering individual and household-level characteristics: 1) the natural log of total land owned by the household, including agricultural land, residential land, and land rented out; 2) a binary indicator if the household owns their home; 3) the number of people residing within the household along with the squared value; 4) number of years of education obtained by the household head, converted to numerical value from a categorical variable representing the highest level of education obtained; 5) age of the household head; 6) a binary indicator if the household head is married; 7) a binary indicator of whether the household head is Female; 8) ratio of dependents (children and adults older than 65) to independents (adults aged 15-65); 9) the natural log of household total expenditures in USD; 10) total value of all household assets, including livestock and energy and non-energy related assets; 11) a binary indicator of if the household received a social cash transfer within the last 12 months from an NGO or government; 12) a binary indicator of if the household owns a modern or improved cookstove, including a gas or electric cookstove, improved charcoal mbaula, improved fixed wood fuel stove, improved portable wood fuel stove, or an improved pellet or briquette stove; 13) a binary indicator if a household owns a traditional cookstove, including a traditional charcoal mbaula or a chitetezo mbaula; 14) a socioeconomic index constructed through a polychoric principal component analysis using socioeconomic indicators from the baseline survey (or the endline survey in the case of new households who were added at endline). In this index, we include a binary indicator if someone in the household is chronically ill or disabled, a binary indicator if members of the household frequently cook only one or no meals per day or go to bed hungry, the number of rooms in the primary dwelling, the roofing material of the primary dwelling, the floor of the primary dwelling, and the household's main water source. A higher index value indicates greater socioeconomic status. The number of rooms in the primary dwelling was not collected for new households added at endline, so we imputed these values using baseline village averages; 15) the number of community group memberships of anyone in the household, including but not limited to agricultural producers' groups, credit or microfinance groups, water users' groups, and religious groups; 16) a financial inclusion index to represent the degree to which households engage with financial tools and institutions, constructed as an integer from 0-3, with 3 indicating the highest level of financial inclusion in our sample. Households were given one point each for meeting each of the following criteria: a) someone in the household has a bank account at a formal institution; b) someone in the household has an informal savings account; or c) someone in the household uses mobile money; 17) a control for household study group. Across all models, we use values of these variables collected at baseline to predict out outcomes of interest for panel and attritor households. However, we use endline values for new household added to the sample at endline, as we did not collect baseline information for these households.

We then run another set of binary logit models to identify factors associated with solar technology ownership at endline. We look across all endline observations, including panel households and new households added only at endline. However, we drop 7 panel household endline observations from our analysis, as their income values were major outliers in the dataset. This drops our endline sample size to 1,224 households. We again run three logit models to identify factors associated with ownership of household level solar technologies, including whether households owned at least one solar home system at endline, whether households owned at least one standalone solar panel at endline, whether households owned at least one solar home system or standalone solar panel at endline. We again cluster standard errors at the village level and include the same set of independent variables in the model. However, we include one additional independent variable: an indicator representing whether the household was promoted to by a solar home system firm in the last 12 months. We report results as odds ratios in Table 6.

Next, we run a binary logit model to identify factors associated with household-level solar technology ownership at any point during the study. We utilize the full sample of baseline and endline observations in this model. Plus, we back out solar technology ownership at baseline for new households added only at endline using the method described above, giving us a sample size of N=2,594. We create three variables to indicate 1) if a household owned at least one solar home system; 2) if a household owned at least one standalone solar panel; and 3) if a household owned at least one solar home system or standalone solar panel. Across each variable, the value of 1 was assigned to each observation when a household owned the given solar technology, and was otherwise assigned a 0. As households were included twice in the sample (one observation each for baseline and endline, except for attritor households who only had one observation), we control for survey wave in the model. We again use the same set of independent variables as in the previous logit models.

To deepen our analysis beyond a binary indicator of solar technology ownership, we run a generalized linear model to identify factors associated with varying levels of total household solar energy capacity. Our dependent variable in this model is the natural log of a household's total solar energy capacity, in Watts. We construct this variable by summing the total solar energy capacity of each solar home system and/or standalone solar panel owned by the household. In this model, we look only at total solar energy capacity of households at endline, as there was a greater sample of solar technology owners at endline. We employ the following equation to define the linear model:

$$Y_j = \beta_0 + \beta_1(Household\ characteristics) + \ \beta_2(Individual\ characteristics) + \varepsilon_j$$

In addition to our models of solar ownership, we run an ordered logit model to determine factors associated with a change in the number of solar technologies a household owned between baseline and endline, to aid our understanding of solar technology adoption. In this model, we look across panel households and new households so that we have two observations for each household. We again back out solar technology ownership of new households added only at endline using the method described above. However, across this sample of panel and new households, we include solely households that did not own solar technologies at baseline. We break our sample into three sub-samples: 1) only households that did not own a solar home system at baseline; 2) only households that did not own a standalone solar panel at baseline; and 3) only households that did not own a solar home system nor a standalone solar panel at baseline. We then run ordered logit models to each sub-sample. In sub-sample 1, we assess if the household adopted a solar home system by endline or remained owning none. In sub-sample 2, we assess if the household adopted a standalone solar panel by endline or remained owning none. In sub-sample 3, we assess if the household adopted either a solar home system or a standalone solar panel by endline or remained owning neither. Across all sub-samples, we apply ordered logit models as our dependent variable, the change in number of devices, is ordinal in nature with a meaningful distances between categories. In sub-sample 1, we drop nine households from the T1 study due to a lack of variation in the data causing multicollinearity and unreliable standard errors. The nine households remain in sub-samples 2 and 3. However, we report results from the model including the nine households in sub-sample 1 in Table A4. We also present results of this model with panel households only (no new households added at endline) in Table A5.

We use the following specification for the ordered logit model:

$$y^* \ = \beta x_i + \varepsilon_i$$

We assume there a continuous latent variable y^* with various threshold points between J=2 groups, where we let Pr(Y_i=2) represent the probability that a household did not adopt by endline (continued to own zero of the given device) and Pr(Y_i=3) represent the probability that a household did adopt at least one of the given solar device by endline.

$$Y_i = \begin{cases} 2 & if \quad -\infty \leq y^* < \tau_1 \\ 3 & if \quad \tau_1 \leq y^* \leq \infty \end{cases}$$

We estimate the probability of each category as the following, using the cumulative logistic distribution:

$$P_i(j) = \begin{cases} \Lambda(\tau_1 - \beta x_i) \\ 1 - \Lambda(\tau_1 - \beta x_i) \end{cases}$$

The ordered logit model includes the same set of independent variables included in the previous models, and we cluster standard errors at the village level. We report results in Table 9.

3.5.3 Factors associated with expanding, maintaining, or contracting solar stock

We further our understanding of solar technology uptake in Malawi by looking at how households in our sample expand, maintain, or contract their supply of solar technologies over time. We again look across panel and new households added at endline, those for which we have information about solar technology ownership at baseline and endline. We subset the data into three sub-samples to look at how households that already own solar adjust their supply of solar technologies over time. We create the following three sub-samples: 1) only households that owned at least one solar home system at baseline; 2) only households that owned at least one standalone solar panel at baseline; and 3) only households that owned at least one solar home system or standalone solar panel at baseline. We then use an ordered logit model for each sub-sample, where our dependent variable is an ordered variable, constructed based on the change in the number of the given type of solar technology between baseline and endline. We therefore assess factors associated with dis-adopting a device (having a smaller number of that device at endline), maintaining the same number of devices (having the same number of that device at endline), or adopting additional devices (having a greater number of that device at endline). We run an additional model where we include only panel households (no new households added at endline) and present our results in Table A6.

In our model specification, we assume a latent variable y^*as follows:

$$y^* = \beta x_i + \varepsilon_i$$

We let there be J=3 categories where we let Pr(Y_i=1) represent the probability that a household dis-adopted at least 1 of the given devices by endline, Pr(Y_i=2) represent the probability that a the household maintained the same number of devices by endline, and Pr(Y_i=3) represent the probability that a household adopted at least one additional device by endline.

$$Y_i = \begin{cases} 1 & if \quad -\infty \leq y^* < \tau_1 \\ 2 & if \quad \tau_1 \leq y^* < \tau_2 \\ 3 & if \quad \tau_2 \leq y^* \leq \infty \end{cases}$$

The probability of each category is therefore modeled as follows, using the cumulative logistic distribution:

$$P_i(j) = \begin{cases} \Lambda(\tau_1 - \beta x_i) \\ \Lambda(\tau_2 - \beta x_i) - \Lambda(\tau_1 - \beta x_i) \\ 1 - \Lambda(\tau_2 - \beta x_i) \end{cases}$$

We report results from this set of models as odds ratios in Table 10.

3.5.4 Regression Diagnostics

We assessed multicollinearity between our independent variables by calculating variance inflation factors (VIF) across all models. In all cases, the VIF value was less than the commonly used threshold of 5, indicating that there is minimal multicollinearity between our set of independent variables. Additionally, we employed Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) as measures to select the best fitting models by evaluating the trade-off between model fit and complexity. We report AIC and BIC values at the bottom of each regression table for comparison.

3.6 Ethical Clearance

The procedures of this study were approved by the University of Michigan (UM) Health Sciences and Behavioral Sciences Institutional Review Board (IRB) (HUM00216379). The UM IRB agreed to provide oversight through a Federal Wide Assurance since no appropriate review board exists. All study materials were translated into Chichewa, the local language of Malawi, and all interviews were conducted in Chichewa. All study participants provided free and informed written consent prior to participating. In the case where a respondent was unable to write, a thumbprint was used in lieu of a written signature. All survey responses were deidentified before data cleaning and analysis.

4. Results

4.1 Range of Solar Products and Capacities

Solar technology ownership is rapidly increasing across Malawi. The Malawi Integrated Household Survey (IHS), a series of population representative surveys conducted by the Government of Malawi, has examined the uptake of solar in Malawi over the past decade. Specifically, the IHS assesses the uptake of solar panels, which the IHS defines as either standalone solar panels or those part of a solar home system. According to the IHS, ownership of solar panels has increased across the country since 2010. Between 2010 and 2020, the percentage of households sampled by the IHS that reported owning a solar panel increased from less than 1% to around 20%. While solar technology adoption is widespread, we see that the level of ownership varies between urban and rural locations, with higher rates of ownership among rural households. In 2020, 10.1% of urban households and 26.1% of rural households reported owning a solar panel. We also see that the rate of adoption is increasing faster in rural locations compared to urban locations. The percentage of urban households that own a solar panel increased by 9.2 percentage points between 2010 and 2020, increasing from 0.6% to 9.8%, while percentage of rural households that own a solar panel jumped by 20.4 percentage points, increasing from 1.3% to 21.7% (Lindsey, 2022).

We also examine the level and rates of solar adoption in our study, though we disaggregate between solar home systems and standalone solar panels. We first compare the percentage of households in our sample that own at least one solar home system, the percentage that own at least one standalone solar panel, the percentage that own at least one of either type, and the percentage that own neither type. We present these percentages across our full sample, as well as disaggregated by study group, in Table 3.

Table 3. Summary statistics of solar ownership

	Study group							
	Already User (T1)		Prospective user (T2)		Control group (C)		Total	
	Baseline	Endline	Baseline	Endline	Baseline	Endline	Baseline	Endline
Own at least 1 solar home system (%)	93.59 (24.57)	96.38 (18.75)	6.46 (24.61)	9.43 (29.24)	9.61 (29.50)	10.81 (31.09)	17.42 (37.94)	19.69 (39.78)
Own at least 1 standalone solar panel (%)	12.82 (33.54)	15.22 (36.05)	19.13 (39.36)	17.08 (37.66)	19.43 (39.61)	19.90 (39.98)	18.51 (38.85)	17.81 (38.28)
Own at least 1 of either device (%)	94.23 (23.39)	96.38 (18.75)	24.14 (42.82)	24.45 (43.01)	26.86 (44.37)	28.01 (44.96)	33.02 (47.04)	33.74 (47.30)
Own no solar devices (%)	5.77 (23.39)	3.62 (18.75)	75.86 (42.82)	75.55 (43.01)	73.14 (44.37)	71.99 (44.96)	66.98 (47.04)	66.26 (47.30)
Observations	156	138	758	679	458	407	1,372	1,224

Mean values presented with standard deviations in parentheses

At baseline, we find that 33.0% of our full sample owned at least one solar home system or standalone solar panel, which is higher than the national level of ownership reported by the Malawi HIS (~20% in

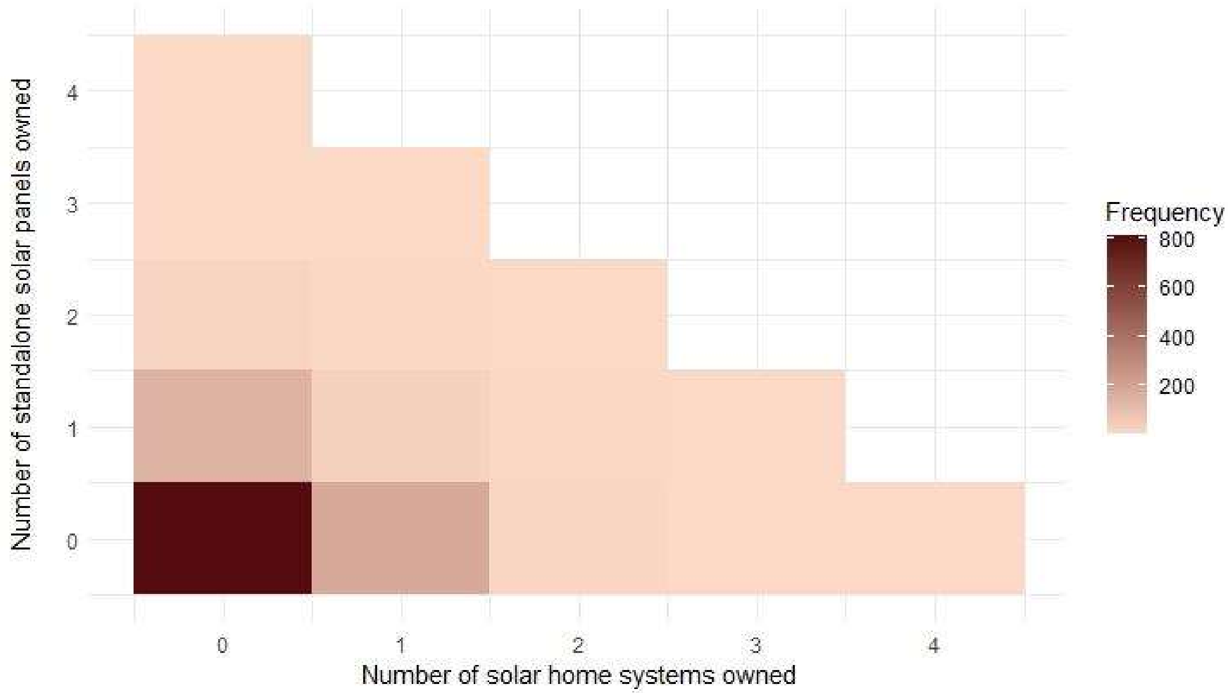
2020). We find that 17.4% of our sample owned at least one solar home system at baseline, and 18.5% owned at least one standalone solar panel. Due to our study design whereby we purposely selected VITALITE customers for our T1 group, 93.6% of our T1 study group reported owning at least one solar home system. Among our prospective user (T2) and control (C) groups, 6.5% and 9.6% owned a solar home system at baseline, with a significantly higher proportion of households in each of those groups owning a standalone solar panel. Through a two-sample t-test between T2 and C groups at baseline, we identify no significant differences between these two groups across these summary statistics.

Between our two survey waves, we see that ownership of either a solar home system or a standalone solar panel across our full sample increased by just 0.7 percentage points from 33.0% to 33.7%. We also see that the percentage of households in our full sample that own at least one solar home system increased by 2.3 percentage points. In particular, in our T2 group, where VITALITE targeted marketing efforts, we see a 2.9 percentage point increase in households with at least one solar home system between baseline and endline.

Overall, we see that owning at least one standalone solar panel ownership is more common in our sample than owning at least one solar home system. However, we find that the percentage of people with at least one of either solar technology in our sample reflects national trends in solar panel adoption and is actually slightly higher. Importantly, while these statistics do shed light on overall levels of solar technology ownership in Malawi, because we specifically added new households at endline that owned solar home systems, we cannot attribute these changes in solar ownership to adoption. We will explore adoption patterns in the following section.

While we assess ownership of at least one solar home system, standalone solar panel, and either type in Table 3, Figure 2 presents the number and combinations of the two types of solar technologies that households owned at endline.

Figure 2. Ownership of multiple solar technology types across households at endline



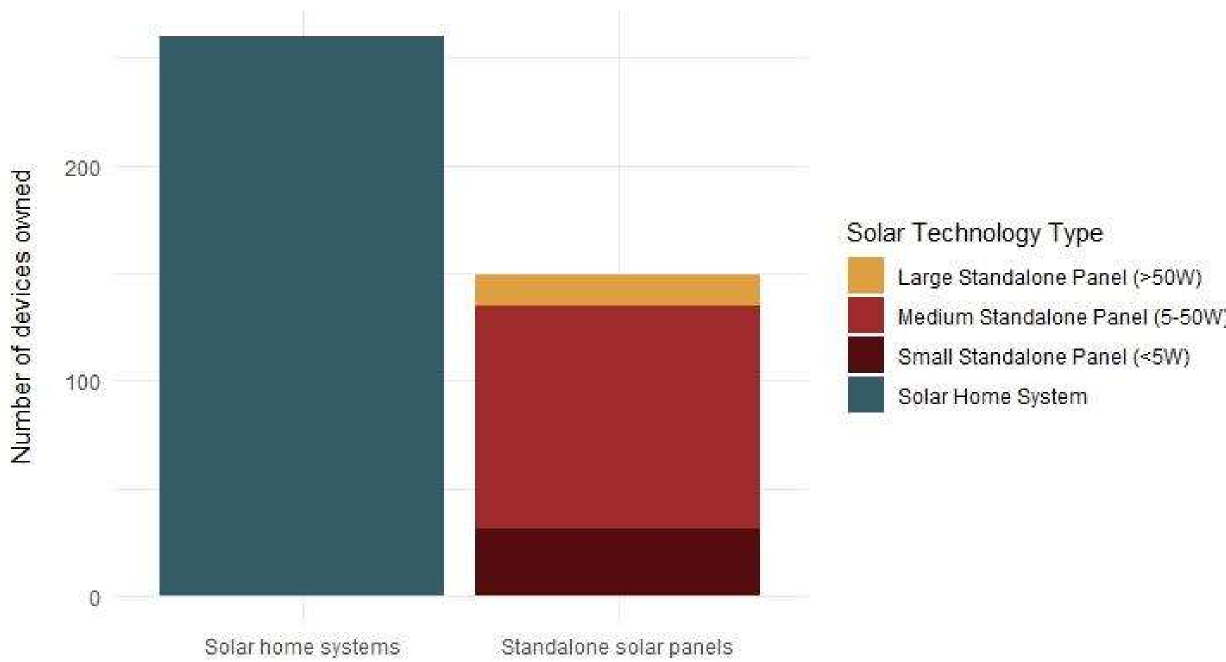
The minimum number of solar home systems any household owned in our sample at baseline was 0, and the maximum was 2. At endline, we find several households with 3 and 4 solar home systems. At baseline and endline, we see that the range of number of standalone solar panels owned by any household across our sample was 4. No households in our sample owned greater than a total of 4 solar devices at either baseline or endline.

In addition, our results show that households do commonly own a mix of solar home systems and standalone solar panels, providing evidence of solar technology's flexibility and modularity. It appears that households commonly adopt more than one solar technology, presumably to increase their household's energy capacity and power more appliances. Notably, a greater proportion of households in our sample are investing in solar home systems than standalone solar panels. Households with many standalone solar panels and fewer solar home systems are less common in our sample.

To deepen our understanding of household-level technology ownership, we assess the various energy capacities of the different types of solar technologies owned in our sample. We classify each individual solar technology owned in our sample into one of the following categories: 1) solar home systems; 2) small standalone solar panels; 3) medium standalone solar panels; and 4) large standalone solar panels. Roughly in line with the Energy Sector Management Assistance Program's (ESMAP) Multi-Tier Framework

(MTF) for measuring electricity access, we define small standalone solar panels as those with less than 5 Watts of energy capacity, medium standalone solar panels as those with 5-50 Watts of energy capacity, and large standalone solar panels as those with more than 50 Watts of energy capacity (Multi-Tier Framework, 2022). We first examine the proportion of each type of solar technology across our sample of solar technology owners at endline, as presented in Figure 3.

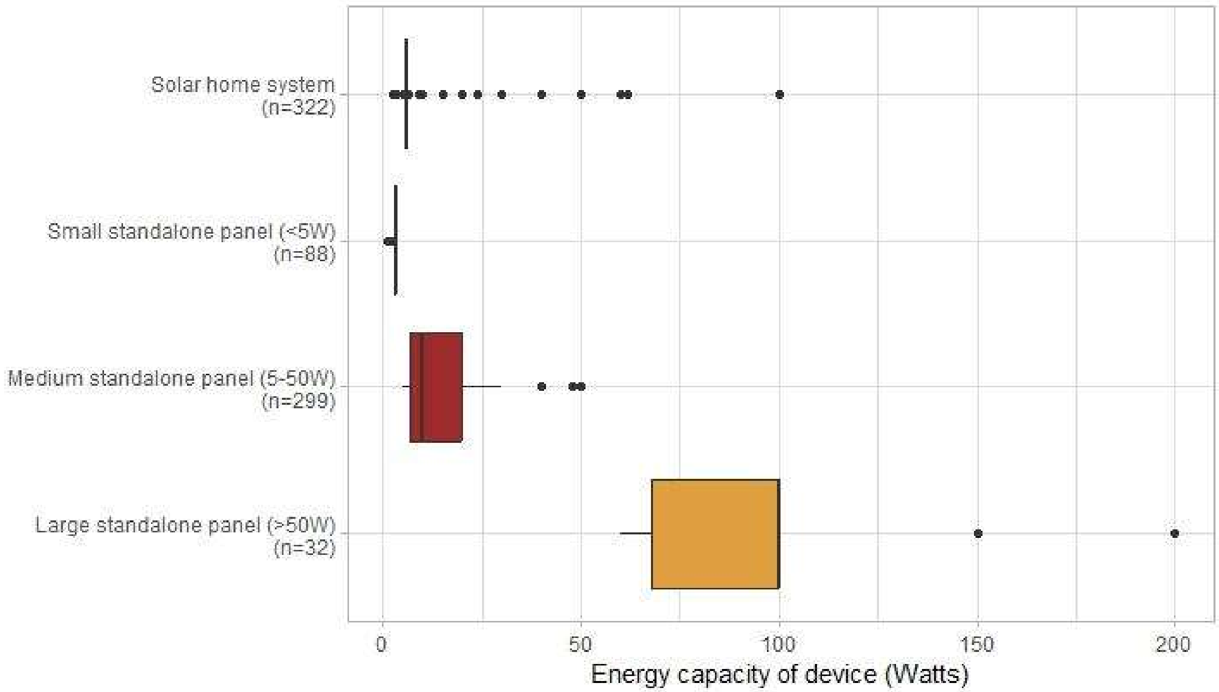
Figure 3. Types of solar technologies owned at endline



The majority of household-level solar technologies owned in our sample are solar home systems, comprising 63.6% of solar technologies owned in our sample at endline. Among all standalone solar panels owned by households in our sample, the most commonly owned size is medium, followed by small, with large panels being highly uncommon across the sample. Medium-sized standalone solar panels, with 5-50W of energy capacity, account for 25.4% of all solar technologies owned in our sample at endline. Small standalone solar panels, with less than 5W of energy capacity, make up 7.6% of the sample of solar technologies. Large standalone panels of greater than 50W account for just 3.4% of solar technologies, making them by far the least common of the four categories of solar technologies.

In addition to understanding the frequency of each different type of solar technology in our sample, we seek to examine the variations in the distributions of energy capacity for each type. Energy capacity distributions for each type of solar device across our sample are presented in Figure 4.

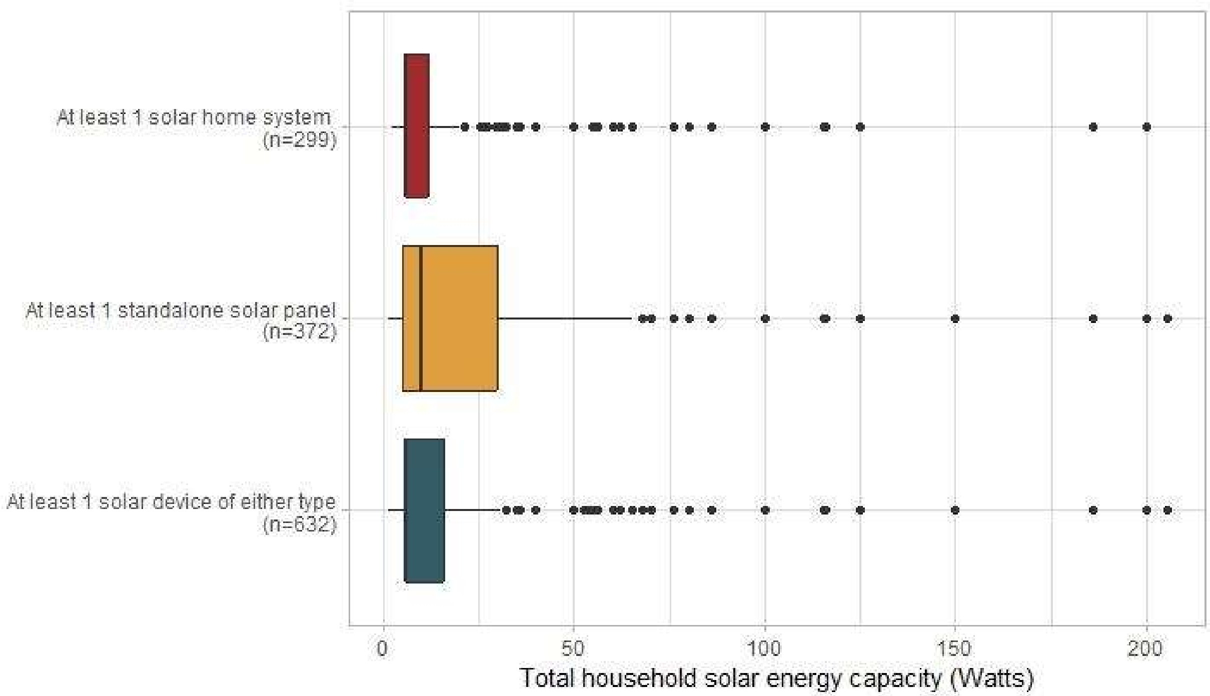
Figure 4. Distribution of energy capacity across types of solar devices owned in our sample



Among solar home systems in our sample, we find that the mean energy capacity hovers around 10W, with a median capacity of 6W. The minimum capacity of any solar home system in our sample is 2.4W and the maximum capacity is 100W. Solar home systems skew right very strongly with lower capacities being significantly more common than high-capacity solar home systems. However, there are several high-capacity outliers. The median energy capacity for small standalone solar panels is 3.25W. Small standalone solar panels have extremely low energy capacities, with a minimum capacity of 1.2W and a maximum of just 4W. Among medium sized standalone solar panels, the energy capacity tends to skew right, with the median energy capacity hovering at 10W and the mean at 16.8W. The majority of medium sized standalone solar panels have an energy capacity between 6.75W and 20W, though there is are several high-capacity outliers with close to 50W of energy capacity. Among large standalone solar panels with energy capacity greater than 50W, the median capacity is 100W, and the mean is 97.1W. Most large standalone solar panels have an energy capacity less than 100W, although the highest capacity standalone solar panel has 200W. With a high proportion of solar home systems and medium sized standalone solar panels in our sample, the average energy capacity of solar technologies across our sample is 15.5W, with a median of 6W. Overall, the energy capacity of solar technologies owned by households in our sample is low.

We further explore the variation in solar energy capacity across our sample of households by examining the total solar energy capacity of each household. For each household, we sum the total solar energy capacity of each solar home system and/or standalone solar panel owned by the household and calculate a variable representing the household's total solar energy capacity, in Watts. We then assess the variation in the distribution of total solar energy capacity across three groups of households: 1) those with at least one solar home system; 2) those with at least one standalone solar panel; and 3) those with at least one of either a solar home system or a standalone solar panel. Results are presented in Figure 5.

Figure 5. Distribution of household total solar energy capacity across our sample



As expected, due to the high proportion of low-capacity solar technologies owned by households in our sample, we see relatively low total energy capacities across sample households. However, we see a high degree of variation in household total solar energy capacity. Our results show that the median total solar energy capacity of households that own at least one of either a solar home system or a standalone solar panel is 6W. However, among those with at least one of either solar technology, the range of total household solar energy capacity spans from 1.5W to 205W. Most of these households have a total solar energy capacity below 30W. We see lower total solar energy capacities among households with at least one solar home system compared to households with at least one standalone solar panel, which may be due to the higher energy capacity of some standalone solar panels in our sample. However, in both cases, the median total household solar energy capacity is less than 25W. Although we see evidence of households adopting several different solar technologies to increase their energy capacities, the total solar energy capacity of households in our sample is extremely low.

4.2 Factors Associated with Household-Level Solar Technology Adoption

Building off of our understanding of the range and capacities of solar devices owned by households in our sample, we now explore the factors associated with household-level solar technology adoption. We first compare mean demographic characteristics across households in each of our study arms to assess their differences and comparability. We calculate mean values across panel households, attritor households, and new households added only at endline. For panel households, we include only baseline values to avoid overweighting panel household characteristics in our study group calculations. We present household characteristics in Table 4.

Table 4. Mean household characteristics across study groups

	Study group			
	Already User (T1)	Prospective user (T2)	Control group (C)	Total
Total land owned (logged acres)	0.93 (0.53)	**0.93** **(0.42)**	**1.00*** **(0.49)**	0.96 (0.46)
Own home (%)	76.28 (42.67)	94.72 (22.37)	93.01 (25.52)	92.06 (27.05)
Household size (number)	4.88 (1.77)	**4.11** **(1.62)**	**4.35*** **(1.88)**	4.28 (1.74)
Household size (number), squared	26.96 (19.28)	**19.54** **(16.33)**	**22.45**** **(20.97)**	21.36 (18.48)
Education of household head (years)	8.74 (3.80)	**5.82** **(3.84)**	**6.39*** **(3.91)**	6.34 (3.96)
Age of household head (years)	40.41 (12.14)	45.49 (17.56)	44.91 (16.92)	44.72 (16.87)
Married (%)	83.97 (36.80)	70.18 (45.77)	71.40 (45.24)	72.16 (44.84)
Female headed household (%)	29.49 (45.75)	33.77 (47.32)	36.90 (48.31)	34.33 (47.50)
Dependency ratio (children + adults>65 / adults 15-65)	0.93 (0.78)	**1.07** **(0.95)**	**0.95*** **(0.94)**	1.02 (0.93)
Annual household expenditures (logged USD)	5.06 (1.06)	4.33 (0.98)	4.30 (1.13)	4.40 (1.07)
Value of household assets (USD)	546.62 (1843.37)	88.81 (241.41)	114.59 (283.76)	149.50 (681.07)

Social cash transfer recipient (%)	2.56 (15.86)	6.07 (23.89)	7.64 (26.60)	6.20 (24.12)
Socioeconomic status index	0.92 (1.15)	**-0.17** **(0.96)**	**-0.03*** **(0.97)**	-0.00 (1.04)
Community group memberships (number)	2.24 (1.98)	**1.71** **(1.58)**	**2.50***** **(2.18)**	2.04 (1.88)
Financial inclusion index	1.46 (0.80)	**0.62** **(0.75)**	**1.00***** **(0.88)**	0.84 (0.85)
Observations	156	758	458	1,372

Mean values presented with standard deviations in parentheses
'*' and bolded text indicates a significant difference in means between T2 and C groups (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$) based on a two-sample t-test of the means

Across our sample households, households are largely male-headed, with a household size of around 4 people, and generally own rather than rent their home. Heads of household are around 45 years old, have about 6 years of education, and are married. In the average household, there is approximately one dependent per each independent adult in the household. Household demographic characteristics look similar across groups, although T1 households are slightly larger and have slightly younger and more educated heads of household compared to T2 and C households. T1 households are also less likely to own their home than T2 or C households. When comparing T2 and C households, T2 households own significantly less land, on average, than C households. T2 households also have fewer members and less education than C households.

Annual household expenditures are matched well across all study groups. The average household has a total asset value of $149.50, though total asset values are substantially higher in T1 households than T2 and C households. 6% of all households reported having received a cash transfer in the last 12 months, indicating ultra-poor status. However, fewer T1 households reported receiving a cash transfer than those in T2 and C groups. Although T2 and C households are matched well on expenditures and asset values, T2 households have a significantly lower socioeconomic index value than C households. Households in T1 have a much higher socioeconomic index value than both T2 and C households.

Across all households, the average household is a part of about two community groups. Furthermore, on average, households score 0.84 on the financial inclusion index, meaning that they meet approximately one of the following criteria: 1) someone in the household has a bank account at a formal institution; 2) someone in the household has an informal savings account; or 3) someone in the household uses mobile money. Social cohesion appears similar across all groups, although T1 households have higher financial inclusion than both T2 and C households.

To determine factors associated with the adoption of household solar devices, we examine individual and household-level factors associated with solar ownership at baseline in 2022, as well as at endline in 2023, and disaggregate between solar home system and standalone solar panel ownership. Table 5 summarizes the results of three sets of binary logit models assessing factors associated with ownership at baseline of: 1) at least 1 solar home system (SHS); 2) at least 1 standalone solar panel; and 3) at least one of either a solar home system or a standalone solar panel.

Table 5. Factors associated with household solar ownership at baseline, presented as odds ratios

	(1) Own at least 1 SHS	(2) Own at least 1 Solar Panel	(3) Own at least 1 of either type
Logged total land owned, in acres	0.764 (0.129)	0.960 (0.175)	0.861 (0.157)
Own home (c.f. do not own)	1.411 (0.687)	1.596 (0.454)	1.896 (0.747)
Household size (number)	1.808** (0.412)	0.765* (0.089)	0.836 (0.103)
Household size (number), squared	0.955* (0.020)	1.022** (0.007)	1.012 (0.010)
Education of household head (years)	1.064 (0.046)	1.035 (0.032)	1.034 (0.027)
Age of household head (years)	1.010 (0.012)	0.982** (0.006)	0.987* (0.006)
Married (c.f. not married)	3.864** (1.696)	2.788*** (0.792)	2.895*** (0.700)
Female-headed household (c.f. male-headed)	3.916** (1.653)	0.572* (0.134)	0.971 (0.190)
Dependency ratio (children + adults>65 / adults 15-65)	1.036 (0.143)	0.936 (0.099)	0.960 (0.099)
Logged annual household expenditures, in USD	1.463* (0.275)	1.187 (0.110)	1.067 (0.099)
Total value of all household assets in USD	1.001* (0.001)	1.000 (0.000)	1.003* (0.001)
Cash transfer recipient (c.f. not recipient)	0.829 (0.450)	1.492 (0.550)	1.347 (0.389)
Socioeconomic status index	1.289	1.388***	1.331***

	(0.208)	(0.138)	(0.110)
Cookstove ownership (c.f. own no cookstove or use basic three-stone fire)			
Own an improved cookstove	0.652	1.899***	1.548*
	(0.310)	(0.309)	(0.312)
Own a traditional cookstove	1.691**	1.257	1.461**
	(0.277)	(0.194)	(0.190)
Community group memberships (number)	0.784***	1.041	0.974
	(0.051)	(0.042)	(0.034)
Financial inclusion index	2.340***	1.299*	1.641***
	(0.318)	(0.137)	(0.175)
Study group (c.f. Already User (T1))			
Prospective user (T2)	0.008***	4.867***	0.042***
	(0.004)	(1.694)	(0.017)
Control group (C)	0.008***	3.741**	0.034***
	(0.004)	(1.657)	(0.015)
Observations	1371	1371	1371
AIC	579.317	1152.116	1160.137
BIC	683.783	1256.582	1264.603

Exponentiated coefficients; Standard errors clustered by village in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Our data suggest that several key factors contribute to the adoption of household solar devices, while they also reveal significant differences across solar type. In assessing the effect of various demographic characteristics, we identify that larger households have greater odds of owning a solar home system, although we find larger households have lower odds of owning a standalone solar panel. As expected, we observe that younger heads of household are more likely to adopt a standalone solar panel, although we do not find a significant association between age and solar home system ownership. Additionally, female heads of household are significantly more likely to adopt a solar home system or standalone solar panel compared to male heads of household. We also find that married heads of household are significantly more likely to adopt a solar home system or standalone solar panel compared to unmarried heads of household. Interestingly, we find no significant association between education level, home ownership status, or total land owned with solar ownership.

With respect to economic factors, our data suggest that a higher socioeconomic index significantly increases the odds of owning a standalone solar panel. We also see a positive correlation between our socioeconomic index and solar home system ownership, though it is not significant. However, we do find that increasing a household's total asset values and/or annual expenditures, indicating greater wealth, makes the household significantly more likely to adopt a solar home system. Similarly, we identify that owning a modern or improved cookstove, compared to not owning a cookstove, is strongly and positively associated with owning a standalone solar panel, though we find that improved cookstove ownership is not a significant determinant of solar home system adoption. Interestingly, we find that ownership of a traditional cookstove, compared to not owning a cookstove, increases the likelihood of owning a solar home system, but not a standalone solar panel. Against our expectations, we find no significant association between solar ownership and being a cash transfer recipient, which we use here as an indicator of extreme poverty.

Indicators of social cohesion and financial inclusion also reveal significant associations with household solar ownership. Interestingly, households with more community group memberships are less likely to adopt solar home systems compared to households with fewer community group memberships. We find no association with community group memberships and standalone panel ownership. Our data suggest that greater financial inclusion is a highly significant positive contributor to household solar device ownership, especially solar home system ownership, which makes sense given that the common payment model for many solar home system kits, pay-as-you-go financing, often requires the use of mobile money.

Results from assessing factors associated with solar technology ownership at endline are presented in Table 6. Our expectation is that results from the baseline and endline ownership models should look similar.

Table 6. Factors associated with household solar ownership at endline, presented as odds ratios

	(1) Own at least 1 SHS	(2) Own at least 1 Solar Panel	(3) Own at least 1 of either type
Logged total land owned, in acres	0.641 (0.155)	0.653* (0.136)	0.587** (0.097)
Own home (c.f. do not own)	0.905 (0.568)	1.167 (0.461)	0.810 (0.376)
Household size (number of members)	2.001* (0.670)	0.968 (0.156)	1.091 (0.260)
Household size (number of members), squared	0.947 (0.029)	1.005 (0.012)	0.992 (0.023)
Education of household head (years)	1.097* (0.048)	0.997 (0.027)	1.033 (0.024)

Age of household head (years)	1.014	0.980**	0.990
	(0.014)	(0.008)	(0.008)
Married (c.f. not married)	3.736**	1.785	2.161*
	(1.603)	(0.647)	(0.795)
Female-headed household (c.f. male-headed)	4.664***	0.487**	0.938
	(2.181)	(0.119)	(0.244)
Dependency ratio (children + adults>65 / adults 15-65)	0.860	0.887	0.847
	(0.126)	(0.074)	(0.089)
Logged annual household expenditures, in USD	1.661*	0.986	1.007
	(0.365)	(0.066)	(0.091)
Total value of all household assets in USD	1.001	1.001***	1.004***
	(0.001)	(0.000)	(0.001)
Cash transfer recipient (c.f. not recipient)	1.244	1.722*	1.910*
	(0.673)	(0.418)	(0.608)
Socioeconomic status index	1.306	1.583***	1.558***
	(0.193)	(0.152)	(0.167)
Cookstove ownership (c.f. own no cookstove or use basic three-stone fire)			
Own an improved cookstove	0.636	1.429*	1.186
	(0.230)	(0.246)	(0.199)
Own a traditional cookstove	1.139	1.040	0.975
	(0.191)	(0.194)	(0.161)
Community group memberships (number)	0.756***	1.042	0.957
	(0.059)	(0.048)	(0.039)
Financial inclusion index	2.524***	1.063	1.546***
	(0.392)	(0.119)	(0.193)
Study group (c.f. Already User (T1))			
Prospective user (T2)	0.006***	4.844***	0.030***
	(0.004)	(1.675)	(0.015)
Control group (C)	0.004***	4.800**	0.026***
	(0.003)	(2.404)	(0.013)
Observations	1223	1223	1223
AIC	569.802	1000.575	1010.456
BIC	671.984	1102.756	1112.637

Exponentiated coefficients; Standard errors clustered by village in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Our results show largely similar results to our model of baseline ownership. In particular, female heads of household continue to be significantly more likely than male heads of household to own a solar home system but significantly less likely to own a standalone solar panel. We also see that younger heads of household are more likely to adopt standalone solar panels, but see no significant effect on solar home system adoption. Furthermore, we continue to see that home ownership status is not correlated with solar ownership, and we see that increasing the total land owned by a household decreases the likelihood that the household will adopt a standalone solar panel. Moreover, we continue to see that a larger household size significantly increases the odds of adopting a solar home system, though we do not see a significant effect on standalone solar panel adoption. We also again see that married heads of household are more likely to adopt a solar home system than unmarried heads of household. In contrast with our baseline analysis, in our endline analysis, we see that more education significantly increases the odds of adopting a solar home system.

Across our economic factors, we continue to see that our socioeconomic index is highly correlated with ownership of standalone solar panels but not with solar home systems. However, we again find that increasing a household's annual expenditures, indicating greater wealth, makes the household significantly more likely to adopt a solar home system. While we found no association between being a cash transfer recipient and solar ownership at baseline, our endline results suggest that being a cash transfer recipient increases the likelihood of owning a standalone solar panel. In our endline model, we continue to see that owning an improved cookstove increases the likelihood of owning a standalone solar panel. However, owning a traditional cookstove is no longer associated with owning a solar home system.

In our endline model, we see that having more community group memberships again decreases the likelihood of owning a solar home system and that greater financial inclusion increases the likelihood of owning a solar home system.

To further our analysis of solar technology adoption in Malawi, we run a set of binary logit models to determine factors associated with ownership of household-level solar technologies at any point during our study period, using our full sample of households. Results are presented in Table 7.

Table 7. Factors associated with household solar ownership across full sample and both study waves, presented as odds ratios

	(1) Own at least 1 SHS	(2) Own at least 1 Solar Panel	(3) Own at least 1 of either type
Logged total land owned, in acres	0.705*	0.822	0.734*
	(0.114)	(0.135)	(0.105)
Own home (c.f. do not own)	1.155	1.348	1.297
	(0.600)	(0.384)	(0.493)

Household size (number of members)	1.912*	0.862	0.945
	(0.482)	(0.103)	(0.140)
Household size (number of members), squared	0.951*	1.013	1.003
	(0.023)	(0.008)	(0.014)
Education of household head (years)	1.080	1.017	1.033
	(0.044)	(0.026)	(0.021)
Age of household head (years)	1.012	0.981**	0.989
	(0.012)	(0.006)	(0.006)
Married (c.f. not married)	3.767***	2.256**	2.492***
	(1.305)	(0.669)	(0.665)
Female-headed household (c.f. male-headed)	4.254***	0.543**	0.956
	(1.710)	(0.122)	(0.197)
Dependency ratio (children + adults>65 / adults 15-65)	0.941	0.906	0.903
	(0.119)	(0.072)	(0.080)
Logged annual household expenditures, in USD	1.559*	1.099	1.038
	(0.287)	(0.102)	(0.082)
Total value of all household assets in USD	1.001*	1.001	1.004***
	(0.001)	(0.001)	(0.001)
Cash transfer recipient (c.f. not recipient)	1.010	1.571	1.568
	(0.510)	(0.379)	(0.381)
Socioeconomic status index	1.297	1.484***	1.428***
	(0.191)	(0.132)	(0.122)
Cookstove ownership (c.f. own no cookstove or use basic three-stone fire)			
Own an improved cookstove	0.645	1.644***	1.365
	(0.254)	(0.219)	(0.233)
Own a traditional cookstove	1.386*	1.167	1.216
	(0.208)	(0.180)	(0.151)
Community group memberships (number)	0.770***	1.039	0.968
	(0.051)	(0.038)	(0.032)
Financial inclusion index	2.423***	1.198	1.589***
	(0.308)	(0.116)	(0.161)
Study group (c.f. Already User (T1))			
Prospective user (T2)	0.007***	4.647***	0.038***
	(0.003)	(1.366)	(0.012)
Control group (C)	0.006***	4.008**	0.031***
	(0.003)	(1.744)	(0.011)
Survey wave (c.f. Baseline)			

Endline	1.499***	0.963	1.066
	(0.167)	(0.075)	(0.088)
Observations	2594	2594	2594
AIC	1116.722	2143.799	2149.259
BIC	1239.803	2266.879	2272.339

Exponentiated coefficients; Standard errors clustered by village in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Compared to our results from our separate analyses of solar technology ownership at baseline and at endline, results from our analysis of solar ownership at any time during the study period reveal similar findings. We continue to see that a larger household size significantly increases the odds of adopting a solar home system, though we do not see a significant effect on standalone solar panel adoption. Moreover, we find that female heads of household are significantly more likely than male heads of household to own a solar home system and significantly less likely to own a standalone solar panel. We again find that younger heads of household are more likely to adopt standalone solar panels compared to older heads of household and that married heads of household are more likely to adopt a solar home system or a standalone solar panel than unmarried heads of household. Like our baseline model, we find that married heads of households are significantly more likely than unmarried households to adopt either a solar home system or a standalone solar panel. Additionally, we continue to find no significant correlation between home ownership status and solar ownership. However, in contrast with our endline analysis, we do not see a significant relationship between education level and solar technology ownership. We also see that increasing the total land owned by a household significantly decreases the odds that they will adopt a solar home system, which we did not find in either of the previous models.

Results across our economics factors look similar to the previous two models. We again see that increasing our socioeconomic index value significantly increases the odds that a household will own a standalone solar panel but not a solar home system. Although, we continue to see that increasing annual household expenditures and total asset value increases a household's likelihood of adopting a solar home system. We also see that owning an improved cookstove increases the likelihood of owning a standalone solar panel and that owning a traditional cookstove increases the likelihood of owning a solar home system.

Like both previous models, our results show that having more community group memberships decreases the likelihood of owning a solar home system and that greater financial inclusion increases the likelihood of owning a solar home system.

We add depth to the study of household-level solar technology adoption by examining factors associated with differences in the overall capacity of a household's supply of solar devices. We seek to understand factors associated with household adoption of greater levels of overall solar energy capacity, as measured in logged Watts. In this model, we look only at total solar energy capacity of households at endline that owned at least one household-level solar device (n=412). Results from a generalized linear regression are presented in Table 8.

Table 8. Factors associated with total energy capacity of household's overall solar stock

	(1) Logged total energy capacity, in Watts
Logged total land owned, in acres	-0.122 (0.088)
Own home (c.f. do not own)	0.122 (0.099)
Household size (number of members)	0.032 (0.067)
Household size (number of members), squared	-0.004 (0.005)
Education of household head (years)	0.009 (0.011)
Age of household head (years)	-0.003 (0.003)
Married (c.f. not married)	0.256* (0.104)
Female-headed household (c.f. male-headed)	0.158** (0.054)
Dependency ratio (children + adults>65 / adults 15-65)	-0.018 (0.035)
Logged annual household expenditures, in USD	0.102* (0.042)
Total value of all household assets in USD	0.000 (0.000)
Cash transfer recipient (c.f. not recipient)	-0.033 (0.148)
Socioeconomic status index	0.087* (0.041)
Cookstove ownership (c.f. own no cookstove or use basic three-stone fire)	

Own an improved cookstove	0.036
	(0.074)
Own a traditional cookstove	0.088
	(0.113)
Solar ownership at endline	
SHS owned at endline (number)	0.486***
	(0.114)
Panels owned at endline (number)	1.022***
	(0.076)
Community group memberships (number)	-0.044*
	(0.018)
Financial inclusion index	0.140*
	(0.066)
Study group (c.f. Already User (T1))	
Prospective user (T2)	0.136
	(0.076)
Control group (C)	-0.052
	(0.094)
Constant	0.369
	(0.251)
Observations	412
AIC	869.846
BIC	958.308

Standard errors clustered by village in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Our data suggest that most household and household head demographic factors are not significant determinants of the capacity of a household's total stock of solar devices. We do find that, on average, households with a married head of household have 25.6% greater overall solar energy capacity compared to unmarried households. We also find that the gender of the household head has a significant effect on total solar energy capacity. Our results show that households with female heads of household have, on average, 15.8% greater overall solar energy capacity compared to households with a male head.

As expected, our data reveal that households with higher socioeconomic index values and/or greater annual expenditures tend to have greater total solar energy capacity. Notably, this suggests that in addition to being more likely or able to adopt a solar device, wealthier households are also more able to access devices with larger capacity and/or adopt more than just one device than less wealthy households. Additionally, our results reveal that both the number of solar home systems and the number of standalone solar panels owned by a household at endline are significantly associated with total household solar capacity. On average across our sample, having one additional solar home system at endline is associated with 48.6% higher overall solar capacity. Moreover, having one additional standalone solar panel at endline is associated with 102% higher overall solar capacity. This important finding reveals that households seem to be expanding their solar stock and achieving greater capacity, in terms of overall Watts, by purchasing additional solar devices. Thus, our data suggests that households are actively purchasing additional devices rather than simply purchasing and relying on one high-capacity product. Here, the modularity of solar home systems and standalone solar panels seems to be a key feature enabling households to achieve greater energy capacity.

We see no significant effect community group memberships or financial inclusion on the overall solar energy capacity of the household.

Building off of our analyses of factors associated with the ownership of different types of solar technologies, as well as households' total solar energy capacity, we seek to explore factors associated specifically with the adoption of solar technologies.

Nearly 10% of households (76) in our sample who did not own any solar technologies at baseline adopted at least one solar device by endline, while the rest continued to own zero solar technologies at endline. Utilizing our two-period study design, we analyze factors associated with household solar adoption by looking across changes in household solar ownership over time. We look across three sets of households who did not own solar technologies at baseline to examine adoption tendencies. We use the following sub-samples: 1) only households who owned zero solar home systems at baseline; 2) only households who owned zero standalone solar panels at baseline; and 3) only households who owned zero of either solar technology type at baseline. By looking across nonowners at baseline, we assess factors associated with initial solar technology adoption. Table 9 presents results of our model assessing adoption over time for nonowners at baseline.

Table 9. Factors associated with change in ownership status between baseline and endline, nonowners at baseline, presented as odds ratios

	(1) SHS	(2) Solar Panel	(3) Either type
Logged total land owned, in acres	0.259*	0.483*	0.373**
	(0.155)	(0.157)	(0.129)
Own home (c.f. do not own)	4.155	0.779	0.459

	(3.730)	(0.513)	(0.239)
Household size (number of members)	2.138	1.432	1.385
	(1.425)	(0.373)	(0.366)
Household size (number of members), squared	0.914	0.977	0.976
	(0.065)	(0.017)	(0.019)
Education of household head (years)	1.120	0.990	1.037
	(0.092)	(0.035)	(0.041)
Age of household head (years)	1.022	0.981	0.999
	(0.023)	(0.011)	(0.012)
Married (c.f. not married)	2.324	1.328	1.703
	(2.440)	(0.605)	(1.264)
Female-headed household (c.f. male-headed)	3.931	0.619	0.972
	(3.038)	(0.232)	(0.570)
Dependency ratio (children + adults>65 / adults 15-65)	0.744	0.836	0.817
	(0.295)	(0.120)	(0.130)
Logged annual household expenditures, in USD	1.383	1.051	1.090
	(0.422)	(0.137)	(0.170)
Total value of all household assets in USD	1.000	1.000	1.001
	(0.000)	(0.000)	(0.001)
Cash transfer recipient (c.f. not recipient)	1.362	1.778	2.075
	(2.082)	(0.854)	(1.029)
Socioeconomic status index	1.915*	2.048***	1.639**
	(0.499)	(0.272)	(0.258)
Cookstove ownership (c.f. own no cookstove or use basic three-stone fire)			
Own an improved cookstove	1.161	0.969	0.890
	(0.753)	(0.344)	(0.286)
Own a traditional cookstove	0.760	0.953	0.815
	(0.350)	(0.247)	(0.185)
Community group memberships (number)	0.688**	1.082	1.006
	(0.099)	(0.072)	(0.071)
Financial inclusion index	2.204***	0.980	1.073
	(0.525)	(0.165)	(0.222)
Was promoted to	10.365***	0.407	2.482*
	(5.706)	(0.208)	(0.927)
Study group (c.f. Already User (T1))			
Control group (C)	0.497	2.104	0.000***
	(0.339)	(1.126)	(0.000)

Prospective user (T2)		3.340***	0.000***
		(1.106)	(0.000)
cut1	10.988***	2.631	-15.758***
	(2.402)	(1.706)	(2.634)
Observations	995	994	812
AIC	225.225	490.196	442.897
BIC	323.280	593.133	532.188

Exponentiated coefficients; Standard errors clustered by village in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results from our regression model identify several factors that significantly affect the likelihood that a non-owning household at baseline will adopt a given solar device. The model finds that neither household size, sex, marriage status, education level, nor gender significantly influence the likelihood of adoption. However, across all three sub-samples, we find that increasing the total land owned by a household significantly decreases the likelihood of adopting a solar technology.

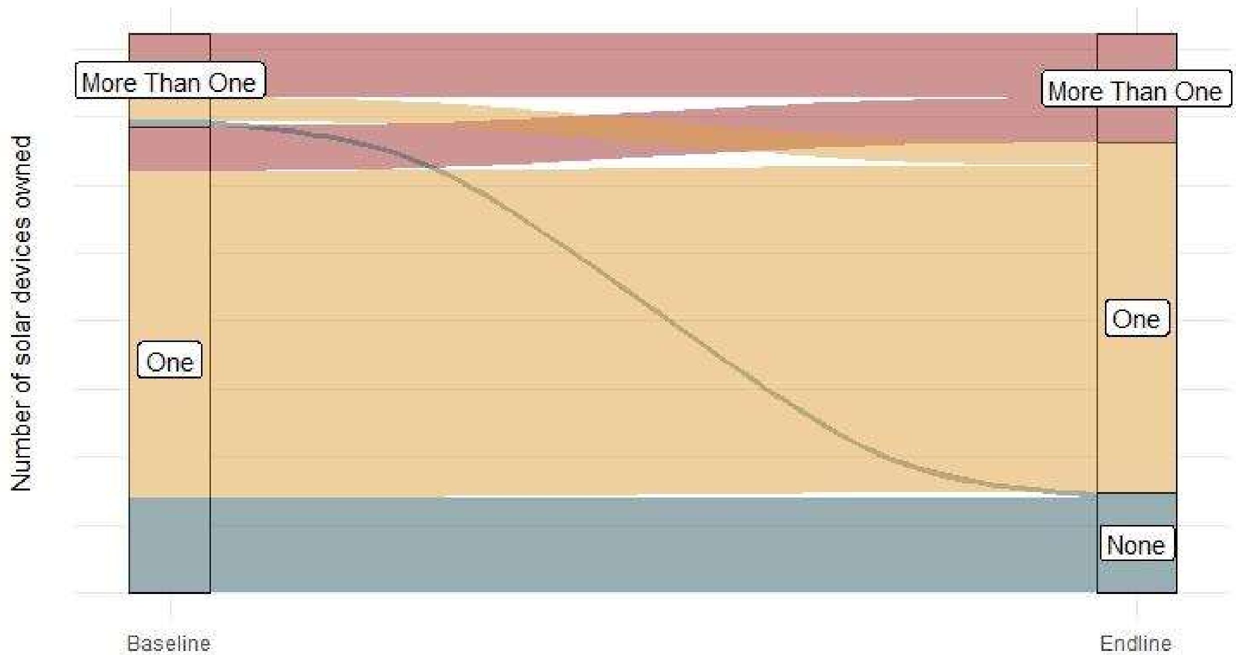
Supporting our previous results, our model continues to show that higher socioeconomic status significantly increases the likelihood that a household will adopt a solar home system, standalone solar panel, or either. We do not find that any of our other economic indicators, annual expenditures, being a cash transfer recipient, or having an improved or traditional cookstove, have a significant effect on the likelihood of solar technology adoption.

Among households that did not own a solar home system at baseline, we find having a higher number of group memberships, indicating greater social capital, significantly decreases the likelihood that a household will adopt a solar home system. We also see that greater financial inclusion significantly increases the likelihood of adopting of a solar home system. Unlike our previous models, we included a variable to indicate whether the household was promoted to by a solar firm between baseline and endline. Interesting, we find that, among households who did not own a solar home system at baseline, being marketed to significantly increases the odds of adopting a solar home system, when compared to those who were not promoted. This finding suggests that marketing can influence the expansion of solar in rural areas.

4.3 Factors Associated with Expanding, Maintaining, or Contracting Solar Stock

One of the most unique features of solar home systems is their modularity. As such, in addition to exploring solar ownership and initial adoption patterns, we deepen our analysis by examining how households change their overall supply, or stock, of solar devices over time. Among households that owned at least one solar home system or standalone solar panel at baseline, a proportion adopted additional solar products by endline, a proportion maintained the same number of solar technologies they owned at baseline, and a proportion dis-adopted some of their solar technologies. Figure 6 displays the evolutions in solar technology ownership between baseline and endline for households that owned at least one solar technology at baseline.

Figure 6. Change in number of solar devices (of either type) owned between baseline and endline, for owners at baseline



Among households that owned at least one solar device at baseline, either a solar home system or a standalone solar panel, 10.5% adopted at least one additional solar technology by endline, 66.4% of households maintained the same number of solar technologies at endline, and 23.1% dis-adopted at least one solar technology by endline. When looking specifically at households that owned at least one solar home system at baseline, 5% adopted one or more additional solar home systems by endline and 9% dis-adopted one or more by endline. Primary reasons for dis-adoption in our survey were: 1) the product was faulty or broken (53%); 2) the household no longer needed the device (20%); or 3) the product was too expensive (13%).

As there is great variability of solar ownership evolutions across our study, we analyze our data to try to understand what contributes to the maintenance, build-out (ie. expansion, additional adoption), or contraction (ie. dis-adoption) of a household's solar stock over time. Making use of our two-period study design, we examine factors associated with a change in household ownership of each type of solar device by looking at maintenance, adoption, and dis-adoption patterns between baseline and endline for households who owned at least one of each given solar device at baseline. Here, we examine solar owners at baseline separately from nonowners at baseline, as households that already owned solar at baseline have characteristics that differ substantially from households who did not own any solar devices at baseline. We theorize that these differences could be an impact attributed to owning solar and want to avoid confounding our results. Moreover, we expect that factors associated with the expansion of a household's solar stock may differ from those associated with a household's initial adoption. Results of this ordered logit model are presented in Table 10.

Table 10. Factors associated with change in ownership status between baseline and endline, owners at baseline, presented as odds ratios

	(1) SHS	(2) Solar Panel	(3) Either type
Logged total land owned, in acres	1.048	0.741	0.669*
	(0.443)	(0.207)	(0.121)
Own home (c.f. do not own)	0.273**	0.364	0.514*
	(0.116)	(0.324)	(0.166)
Household size (number of members)	1.529	0.854	1.131
	(0.542)	(0.211)	(0.193)
Household size (number of members), squared	0.990	1.011	0.997
	(0.031)	(0.013)	(0.010)
Education of household head (years)	1.014	0.938	0.958*
	(0.052)	(0.031)	(0.019)
Age of household head (years)	1.040	0.988	0.998
	(0.023)	(0.010)	(0.008)
Married (c.f. not married)	0.582	1.970	1.485
	(0.249)	(0.958)	(0.455)
Female-headed household (c.f. male-headed)	1.306	0.640	1.065
	(0.781)	(0.239)	(0.301)
Dependency ratio (children + adults>65 / adults 15-65)	0.448*	1.060	0.850
	(0.172)	(0.212)	(0.132)
Logged annual household expenditures, in USD	1.958**	0.886	1.195
	(0.470)	(0.150)	(0.161)
Total value of all household assets in USD	1.000**	1.001	1.001
	(0.000)	(0.001)	(0.001)
Cash transfer recipient (c.f. not recipient)	8.443***	1.933	2.101
	(5.342)	(1.462)	(1.204)

Socioeconomic status index	0.717	1.357*	1.353*
	(0.147)	(0.170)	(0.186)
Cookstove ownership (c.f. own no cookstove or use basic three-stone fire)			
Own an improved cookstove	0.710	1.107	0.993
	(0.279)	(0.263)	(0.264)
Own a traditional cookstove	0.615	0.777	0.800
	(0.230)	(0.203)	(0.151)
Solar ownership at baseline			
SHS owned at baseline (number)	0.074**		
	(0.064)		
Panels owned at baseline (number)		0.686	
		(0.164)	
Solar devices of either type owned at baseline (number)			0.441**
			(0.139)
Community group memberships (number)	0.988	0.906	0.883*
	(0.166)	(0.052)	(0.045)
Financial inclusion index	1.146	0.886	1.204
	(0.338)	(0.149)	(0.161)
Was promoted to	2.573	1.198	1.721*
	(1.525)	(0.502)	(0.445)
Study group (c.f. Already User (T1))			
Prospective user (T2)	0.160***	1.856	0.440**
	(0.083)	(1.181)	(0.130)
Control group (C)	0.413	4.688*	0.826
	(0.416)	(3.115)	(0.258)
cut1	-1.377	-3.059	-2.194
	(2.143)	(2.554)	(1.227)
cut2	5.633*	0.239	1.734
	(2.524)	(2.504)	(1.223)
Observations	219	229	411
AIC	214.575	418.441	664.695
BIC	292.524	497.416	757.122

Exponentiated coefficients; Standard errors clustered by village in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

As expected, our data suggest that the factors that contribute to a household's initial adoption of a solar device differ from the factors that contribute to a household continuing to expand their stock of solar devices. Our results show that few factors across household and household head demographic characteristics are significantly associated with changes in household solar ownership over time in our sample. Neither household size, age, marriage status, nor gender of household head are significant determinants of changes in household solar stock over time. However, our results show that increasing the amount of land area owned by a household significantly increases the odds that they will maintain or contract their supply of solar technologies. We see that home owners are significantly more likely to maintain or contract their systems when compared to renters. In addition, we find that increasing the education level of the household head increases the likelihood that the household will maintain the number of solar technologies they had at baseline.

When looking at economic factors, we find further evidence to support that socioeconomic status is a primary determinant of solar adoption. The results of our model show that higher socioeconomic status significantly increases the likelihood that a household will maintain or build-out their stock of solar devices. We also find that increasing a household's annual expenditures makes the household more likely to maintain or expand their stock of solar technologies, as does increasing a household's total asset value. Similarly, being a social cash transfer recipient significantly increases the likelihood that the household will maintain or expand their solar stock. Interestingly, we find that owning a greater number of solar home systems at baseline increases the odds that a household will dis-adopt at least one solar home system. Our results suggest that there may be an ideal capacity level that households reach at which they no longer seek to expand their systems. There may also be logistical or financial barriers to expanding beyond a certain capacity or number of devices causing them to dis-adopt.

Consistent with our previous models, we find that households with greater social capital are more likely to maintain or contract their supply of solar technologies. We see no significant influence on changes in solar stock from our financial inclusion index, suggesting that financial inclusion may only be important for the very first, initial adoption, likely due to the initial need for mobile money. When looking at the effect of promoting solar home systems, consistent with our previous findings, we find that promotion is significantly associated with an increased likelihood of maintaining the same number of solar technologies or adopting additional devices between baseline and endline.

5. Discussion

5.1 Key Findings

5.1.1 Range of solar products and capacities

Our study identifies several insights regarding solar technology uptake in Malawi. Firstly, we see solar technology adoption in our study area mirroring national levels of adoption within rural locations, and even outpacing it. Across our sample, the percentage of households with at least one solar home system or standalone solar panel at baseline was 33%, providing evidence that solar technologies are rapidly expanding across the country, even into remote locations.

Our study also highlights important distinctions between types of solar technologies. We find that ownership of at least one standalone solar panel is more common in our sample than the ownership of at least one solar home system. Nevertheless, we find evidence that many households are utilizing the modularity feature of solar technologies by adopting several household-level solar technologies of different types and capacities, creating a complex stock of solar technologies within the household.

Across our sample, we find that solar home systems and medium-sized standalone solar panels (5-50W) were the two most common types of household-level solar technologies. Small standalone solar panels (<5W) were uncommon in our sample, and large standalone solar panels (>50W) were even more uncommon. When assessing the solar energy capacity of the solar technologies own across our sample, we identified that the capacities skewed very low, with the median energy capacity across all devices being just 6W. Furthermore, our data reveal that, although it is common for households to own multiple types of solar technologies, the total household solar energy capacity (sum of energy capacities across all solar technologies) of the vast majority of households is less than 50W. Within the framework of working to achieve universal energy access, these findings highlight the importance of understanding the variations across solar technologies with different energy capacities. The majority of solar technologies being adopted by households in our study area have extremely limited energy capacities, though the overall range of energy capacities is quite expansive.

5.1.2 Factors associated with household-level solar technology adoption

Our analysis reveals important findings related to the adoption of household-level solar technologies. First, our study finds that factors contributing to solar device adoption differ significantly between solar home systems and standalone solar panels. Across demographic characteristics of the household and household head, we find differences across total land owned, household size, and gender and age of the household head. Although not significant in all of our models, we identify that owning more land tends to decrease the likelihood of adopting a solar home system, but no significant impact on standalone solar panel adoption. Additionally, we see a positive correlation between household size and solar home system ownership and a negative correlation with standalone solar panel ownership, although significance levels vary between models. We also see a negative correlation between age and standalone solar panel ownership, but no correlation with solar home system ownership. Interesting, we also find female heads of household to be significantly more likely than male heads of household to own or adopt a solar home system and significantly less likely to own or adopt a standalone solar panel. When looking at cookstove ownership as a predictor of solar technology ownership, we find that owning an improved cookstove increases the likelihood of owning a standalone solar panel and that owning a traditional cookstove increases the likelihood of owning a solar home system.

Second, our data identify several significant predictors of household-level solar technology ownership. As noted above, we find that total land owned, household size, education level, marriage status, and gender of household head are all significant predictors of solar technology ownership. Consistent with the literature, our results showed mixed findings on the impact of the household head's education level and age on solar adoption. Our results also showed mixed findings on the effect of social cash transfers, though they appear to be positively corelated with standalone solar panel adoption. Across our models, we see a significant, positive association between our socioeconomic index variable with standalone solar panel adoption. We find mixed results on the impact of socioeconomic index on solar home system adoption. However, we find total household expenditures, total asset values, and cookstove ownership positively impact solar home system adoption, suggesting that socioeconomic status is a significant determinant of adoption.

Interestingly, we find that community group membership, which we include here to represent households' degree of social cohesion, is negatively correlated with solar home system adoption and with expansion of households' overall solar stock. Importantly, our data reveals a new finding that financial inclusion is a significant determinant of initial adoption of solar home systems, which is likely due to the need for mobile money or formal or informal bank accounts to purchase a solar device, particularly when financing through a pay-as-you-go model. Importantly, we also find that being promoted to by a solar company significantly increases the likelihood of adopting a solar home system.

5.1.3 Factors associated with expanding, maintaining, or contracting solar stock

Across our sample, we find evidence of households expanding, maintaining, and contracting their supply of solar technologies over time. Among households that owned at least one solar device at baseline, either a solar home system or a standalone solar panel, 10.5% adopted at least one additional solar technology by endline, 66.4% of households maintained the same number of solar technologies at endline, and 23.1% dis-adopted at least one solar technology by endline.

Through our assessment of the change in number of solar devices over time, we find that the factors that contribute to a household's initial adoption of a solar device differ from the factors that contribute to a household continuing to expand their stock of solar devices. Our data reveal that decreasing the amount of land area owned by a household, owning a home rather than renting, and more years of education increase the likelihood of a household maintaining their stock of solar device over time. Importantly, we also find that socioeconomic status is a key factor that increases the likelihood a household will build-out their supply of solar technologies over time. Household total asset values, as well as annual household expenditures are also positively associated with maintaining household solar stock over time.

5.2 Policy Implications

Our results reveal several important policy implications for rural electrification efforts. By examining the types of solar technologies being adopted in Malawi, as well as the variations in capacities, our study identifies a need for a more nuanced analysis of the uses and impacts of household-level solar technologies by capacity level. Moreover, we find that the majority of solar technologies across our sample have extremely limited capacity. As such, more targeted efforts by donors and government are needed to support households in rural areas where grid connectivity is unavailable to be able to afford and access greater capacity solar technologies.

In addition, as a result of our findings that socioeconomic status is a key determinant of solar technology adoption among households in our sample, policy interventions should target the lowest-income households to ensure they can access the technology. While the Government of Malawi is promoting decentralized technologies, like solar home systems and standalone solar panels, as low-cost alternatives to grid connection, many households are still unable to afford them. Financial support is needed to directly help low-income residents access the technology. In our study, we find some evidence that social cash transfers may facilitate adoption, so these may be an effective option. We also find evidence that financial inclusion is a critical determinant of adoption. As such, interventions should provide support for households to improve their financial inclusion, including gaining access to mobile money and formal or informal bank accounts in order to access household-level solar technologies and gain energy access. Moreover, our results show that promotion, or marketing, by a solar company is effective at increasing the likelihood that a household adopts a solar technology. The government should continue to support the private sector solar market in order to increase the reach of household-level solar into rural areas.

While more support is needed to support low-income households access solar technologies, additional support is needed to assist households in maintaining and expanding their stock of solar technologies over time. In our study, we see substantial amount of dis-adoption, primarily due to issues of maintenance and affordability. Efforts are needed to improve maintenance services for rural households to ensure they can continue using their solar technologies for the long-term. Moreover, additional research should be conducted to assess the long-term impacts of household-level solar technology adoption, especially in comparison to grid connectivity, to ensure household solar technology is an effective long-term strategy for rural electrification.

5.3 Limitations

Our study has several limitations. First, the data collected during the household surveys was self-reported, which can be subject to error. When collecting information about solar technology type and capacity, enumerators were instructed to ask respondents to show them the device in order to ensure the most accurate information was collected. However, it was not always possible to see the solar device; for example, if a standalone solar panel was located on the roof. We did attempt to minimize error by asking respondents to tell us the approximate physical size of each solar panel (small, medium, or large) based off a reference (e.g., a small panel was anything the size of or smaller than the folder that the enumeration team carried around to interviews; large panels were anything larger than half of a doorway). While cleaning the data, our team compared the self-reported capacity data with the physical sizes reported and saw very little obvious errors. At endline, we also collected information on the brand and type of each solar home system owned by our study households. As a result, we were able to cross-check the energy capacity of the branded solar home system with the self-reported data. We again saw minimal errors.

Additionally, due to the change in our study design at endline, whereby we selected to add 93 new households who owned solar home systems in order to make up for attrition and increase our sample size of solar home system owners, we were not able to collect baseline values for these households. As a result, we used endline values for these households across all of our independent variables. We do not expect that these would change substantially from baseline to endline, though they may be somewhat influenced by our outcome of interest and may slightly bias our results. We were able to back out the ownership status of these household at baseline from their endline questionnaire responses. We asked households at endline to report each solar device they currently owned and how long they had had the device and therefore assumed that any devices at least 12 months old were also owned at baseline. Although this method of interpolation should be mostly accurate, it assumes respondents remembered exactly how long they owned their current solar technologies. Furthermore, by not interviewing these households at endline, we were unable to collect information about dis-adopted solar technologies, which may skew our sample.

Moreover, due to our non-random sampling technique, there are significant differences in demographic characteristics between all three of our study groups. Although the differences are minimal between T2 and C households, the lack of randomization can cause our coefficient and errors to be biased.

Lastly, our regression models primarily consider demand side factors including household demographics and socioeconomic status. We use a study area level dummy variable, as well as cluster errors at the village level, to control for a range of unobservable supply side factors. However, we do not explicitly examine supply side factors in our analysis.

6. Conclusion

Our study fills multiple gaps in the existing literature of household solar adoption in Africa. Notably, our study examines households in Malawi where only limited research on household-level solar uptake has been conducted. Moreover, we specifically look to rural areas in Malawi, where grid connectivity is very limited, which again is rarely studied in the literature. We further contribute to the literature as our study uniquely compares across two different types of solar devices popular in the region, solar home systems and standalone solar panel, to identify critical factors that influence whether households adopt each particular type of solar device, or both. Moreover, we add nuance by examining differences in the energy capacity of the solar technologies across our sample, along with households' overall solar energy capacities. Furthermore, our study recognizes modularity as a key feature of household-level solar technologies and therefore explores under what conditions households expand, maintain, or contract their overall supply of solar technologies over time. Using our study's two-period design, we conduct a rigorous quantitative assessment of changes in solar technology ownership over time.

Our study highlights several key findings and implications for rural electrification initiatives. We find that households in Malawi are adopting a mix of solar technologies that help them achieve greater energy capacity. However, our data reveals that the energy capacity of the majority of household-level technologies are extremely low, meaning even those households with several solar technologies have very limited capacity. As a result, we identify a need for more research into the impacts of solar technology, by capacity level, as well as more targeted efforts by donors and government to help households afford and access greater capacity solar technologies.

When assessing factors associated with household-level solar technology ownership, we identify a set of demographic characteristics that are significantly associated with ownership, including household size, gender and age of household head, and marriage status. Most importantly, our data suggest that low socioeconomic status is a major barrier to solar technology adoption. As such, we recommend donors and government provide more financial support to low-income residents to enable them to access these technologies.

Lastly, we find substantial evidence that households change their solar ownership overtime, whether by adopting additional solar technologies or dis-adopting. We again identify various indicators of socioeconomic status as significant factors associated with increasing the likelihood that a household expands their supply of solar technologies. As a result, we suggest that greater financial support is needed to not only enable households to purchase household-level solar technologies, but to be able to maintain and build-out their stock of solar technologies over time in order to achieve a sufficient level of energy capacity.

Overall, it is evident that household-level solar technologies are becoming increasingly popular across Malawi and are enabling many rural households to access electricity for the first time. While household-level solar appears to have immense potential for electrifying rural households, there are several key challenges that may impede advancement towards universal electrification. In order for household-level solar technology to be an effective electrification strategy in the long-term, donors and government must provide additional support to the lowest-income households and must continue to provide support until all households are able to generate a sufficient level of energy that allows them to, at the very least, meet their basic needs.

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8. Appendices

Table A1. List of active standalone solar companies in Malawi in 2022

Solar Product Provider	
1	VITALITE
2	Yellow
3	Sunny Money
4	Zuwa Energy
5	Solar Works
6	Sen Solar Engineering
7	Sonlite Solar
8	Recapo
9	Sky Energy
10	Danforth Solar
11	Econo Power
12	Team Planet
13	Electricity for All
14	Powered By Nature
15	M-PAYG/x-solar
16	Green Impact Technologies
17	Kumudzi Kuwale
18	Total Malawi

Table A2. Characteristics of study area for each study arm

	Current Users (T1)	**Prospective Users (T2)**	**Control Group (C)**
Traditional Authority	Chadza, Kalumba, Chiseka	Mazengera	Chimutu
Distance from Lilongwe Center (Euclidean)	17.0 km	21.1 km	21.9 km
Distance from Lilongwe Center (road distance and estimated travel time)	23.7 km; 40 min	26.5 km; 1 hour 5 min	34.6 km; 1 hour
Population density in 5 km (persons/sq. km)	212	252	301
High voltage grid* runs through centroid	No	Yes	Yes
Medium voltage grid* runs through centroid	Yes	Yes	Yes

% of population within 1 km of medium voltage grid*	62.0	15.5	22.0
Number of study villages	7	11	10

*Grid data from Facebook "Medium-Voltage Grid (Predictive)" Downloaded July 2022. https://energydata.info/dataset/medium-voltage-distribution-predictive

Table A3. Factors associated with household solar ownership at baseline, baseline observations of panel and attritor households only, presented as odds ratios

	(1) Own at least 1 SHS	(2) Own at least 1 Solar Panel	(3) Own at least 1 of either type
Logged total land owned, in acres	0.615 (0.189)	1.057 (0.216)	0.835 (0.180)
Own home (c.f. do not own)	5.948 (6.790)	2.067 (0.786)	3.284^{*} (1.881)
Household size (number)	3.030^{*} (1.440)	0.717^{**} (0.090)	0.744^{*} (0.102)
Household size (number), squared	0.900^{*} (0.039)	1.025^{**} (0.008)	1.019^{*} (0.009)
Education of household head (years)	1.149^{*} (0.076)	1.025 (0.032)	1.034 (0.031)
Age of household head (years)	0.986 (0.014)	0.979^{***} (0.006)	0.980^{**} (0.006)
Married (c.f. not married)	3.546^{*} (2.051)	2.227^{**} (0.674)	2.548^{***} (0.689)
Female-headed household (c.f. male-headed)	3.174^{*} (1.530)	0.440^{**} (0.115)	0.641^{*} (0.131)
Dependency ratio (children + adults>65 / adults 15-65)	0.979 (0.196)	0.952 (0.103)	0.952 (0.103)
Logged annual household expenditures, in USD	1.301 (0.288)	1.132 (0.112)	1.035 (0.097)
Total value of all household assets in USD	1.000 (0.001)	1.000 (0.000)	1.002^{*} (0.001)
Cash transfer recipient (c.f. not recipient)	1.296 (1.120)	1.602 (0.604)	1.700 (0.554)
Socioeconomic status index	2.712^{***} (0.662)	1.545^{***} (0.158)	1.547^{***} (0.150)
Cookstove ownership (c.f. own no cookstove or use basic three-stone fire)			
Own an improved cookstove	0.756	1.786^{***}	1.762^{**}

	(0.537)	(0.303)	(0.353)
Own a traditional cookstove	1.956**	1.253	1.445*
	(0.474)	(0.209)	(0.210)
Community group memberships (number)	0.904	1.041	1.006
	(0.103)	(0.042)	(0.041)
Financial inclusion index	1.622*	1.380*	1.505***
	(0.329)	(0.176)	(0.185)
Study group (c.f. Already User (T1))			
Prospective user (T2)	0.000***	5.893***	0.003***
	(0.000)	(2.335)	(0.002)
Control group (C)	0.000***	4.662**	0.002***
	(0.000)	(2.181)	(0.001)
Observations	1279	1279	1279
AIC	295.612	1052.05	990.829
BIC	398.689	1155.127	1093.906

Exponentiated coefficients; Standard errors clustered by village in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A4. Factors associated with change in ownership status between baseline and endline, nonowners at baseline, with nine T1 households included in (1) SHS model

	(1) SHS	(2) Solar Panel	(3) Either type
Logged total land owned, in acres	0.263*	0.483*	0.373**
	(0.156)	(0.157)	(0.129)
Own home (c.f. do not own)	4.060	0.779	0.459
	(3.618)	(0.513)	(0.239)
Household size (number of members)	1.934	1.432	1.385
	(1.214)	(0.373)	(0.366)
Household size (number of members), squared	0.924	0.977	0.976
	(0.061)	(0.017)	(0.019)
Education of household head (years)	1.120	0.990	1.037
	(0.091)	(0.035)	(0.041)
Age of household head (years)	1.022	0.981	0.999
	(0.023)	(0.011)	(0.012)
Married (c.f. not married)	2.320	1.328	1.703
	(2.417)	(0.605)	(1.264)
Female-headed household (c.f. male-headed)	3.851	0.619	0.972
	(2.973)	(0.232)	(0.570)
Dependency ratio (children + adults>65 / adults 15-65)	0.751	0.836	0.817
	(0.295)	(0.120)	(0.130)

Logged annual household expenditures, in USD	1.360	1.051	1.090
	(0.408)	(0.137)	(0.170)
Total value of all household assets in USD	1.000	1.000	1.001
	(0.000)	(0.000)	(0.001)
Cash transfer recipient (c.f. not recipient)	1.363	1.778	2.075
	(2.066)	(0.854)	(1.029)
Socioeconomic status index	1.915*	2.048***	1.639**
	(0.500)	(0.272)	(0.258)
Cookstove ownership (c.f. own no cookstove or use basic three-stone fire)			
Own an improved cookstove	1.159	0.969	0.890
	(0.751)	(0.344)	(0.286)
Own a traditional cookstove	0.761	0.953	0.815
	(0.350)	(0.247)	(0.185)
Community group memberships (number)	0.690**	1.082	1.006
	(0.099)	(0.072)	(0.071)
Financial inclusion index	2.201***	0.980	1.073
	(0.521)	(0.165)	(0.222)
Was promoted to	10.324***	0.407	2.482*
	(5.633)	(0.208)	(0.927)
Study group (c.f. Already User (T1))			
Prospective user (T2)	0.000***	3.340***	0.000***
	(0.000)	(1.106)	(0.000)
Control group (C)	0.000***	2.104	0.000***
	(0.000)	(1.126)	(0.000)
cut1	-16.007	2.631	-15.758***
	(.)	(1.126)	(2.635)
Observations	1004	994	812
AIC	225.242	490.196	444.897
BIC	323.477	593.133	538.887

Exponentiated coefficients; Standard errors clustered by village in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A5. Factors associated with change in ownership status between baseline and endline, nonowners at baseline, panel households only, presented as odds ratios

	(1) SHS	(2) Solar Panel	(3) Either type
Logged total land owned, in acres	0.234	0.423*	0.368**
	(0.177)	(0.147)	(0.125)

Own home (c.f. do not own)	1.700 (1.529)	0.549 (0.291)	0.390 (0.189)
Household size (number of members)	4.222* (2.766)	1.532 (0.427)	1.556 (0.435)
Household size (number of members), squared	0.857 (0.069)	0.972 (0.019)	0.968 (0.022)
Education of household head (years)	1.113 (0.097)	0.979 (0.033)	1.025 (0.042)
Age of household head (years)	1.031 (0.025)	0.984 (0.011)	1.001 (0.012)
Married (c.f. not married)	4.504 (4.632)	1.591 (0.804)	2.296 (1.600)
Female-headed household (c.f. male-headed)	5.132* (4.048)	0.734 (0.304)	1.198 (0.642)
Dependency ratio (children + adults>65 / adults 15-65)	0.675 (0.347)	0.883 (0.119)	0.804 (0.135)
Logged annual household expenditures, in USD	1.531 (0.523)	1.095 (0.157)	1.114 (0.186)
Total value of all household assets, in USD	0.999 (0.001)	1.001 (0.000)	1.000 (0.001)
Cash transfer recipient (c.f. not recipient)	1.466 (2.456)	1.685 (0.792)	2.159 (1.099)
Socioeconomic status index	2.186* (0.694)	1.931*** (0.334)	1.756*** (0.270)
Cookstove ownership (c.f. own no cookstove or use basic three-stone fire)			
Own an improved cookstove	1.100 (0.684)	0.917 (0.342)	1.020 (0.309)
Own a traditional cookstove	0.917 (0.405)	1.026 (0.274)	0.855 (0.191)
Community group memberships (number)	0.799 (0.104)	1.081 (0.071)	1.053 (0.075)
Financial inclusion index	1.730* (0.395)	1.032 (0.188)	0.952 (0.227)
Was promoted to	8.181** (5.313)	0.452 (0.203)	2.015 (0.792)
Study group (c.f. Already User (T1))			
Control group (C)	0.316 (0.189)	2.067 (1.227)	0.592 (0.166)

Prospective user (T2)		3.819***	
		(1.509)	
cut1	13.205***	3.160	3.161
	(2.415)	(1.765)	(2.241)
Observations	986	922	799
AIC	203.561	467.932	423.778
BIC	301.434	569.290	517.445

Exponentiated coefficients; Standard errors clustered by village in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A6. Factors associated with change in ownership status between baseline and endline, owners at baseline, panel households only

	(1) SHS	(2) Solar Panel	(3) Either type
Logged total land owned, in acres	1.053	0.638	0.571*
	(0.629)	(0.193)	(0.139)
Own home (c.f. do not own)	0.330*	0.824	0.533
	(0.186)	(1.208)	(0.221)
Household size (number of members)	1.497	0.820	1.119
	(0.760)	(0.167)	(0.191)
Household size (number of members), squared	0.985	1.011	0.998
	(0.027)	(0.011)	(0.010)
Education of household head (years)	1.068	0.913*	0.952*
	(0.073)	(0.034)	(0.021)
Age of household head (years)	1.048	0.984	0.996
	(0.026)	(0.010)	(0.009)
Married (c.f. not married)	0.444	0.998	0.935
	(0.230)	(0.445)	(0.269)
Female-headed household (c.f. male-headed)	1.201	0.272***	0.617
	(1.195)	(0.090)	(0.202)
Dependency ratio (children + adults>65 / adults 15-65)	0.282***	1.060	0.816
	(0.085)	(0.202)	(0.129)
Logged annual household expenditures, in USD	1.839	0.820	1.211
	(0.719)	(0.131)	(0.157)
Total value of all household assets in USD	1.000***	1.001	1.000
	(0.000)	(0.001)	(0.000)
Cash transfer recipient (c.f. not recipient)	13.845***	2.093	2.433
	(11.047)	(1.443)	(1.259)
Socioeconomic status index	0.921	1.610**	1.539**
	(0.231)	(0.255)	(0.217)

Cookstove ownership (c.f. own no cookstove or use basic three-stone fire)			
Own an improved cookstove	0.998	1.067	0.980
	(0.442)	(0.251)	(0.240)
Own a traditional cookstove	0.808	0.720	0.775
	(0.458)	(0.176)	(0.167)
Community group memberships (number)	1.095	0.925	0.922
	(0.227)	(0.049)	(0.057)
Financial inclusion index	0.730	0.974	1.127
	(0.212)	(0.166)	(0.153)
Was promoted to	3.535	1.146	1.685
	(3.205)	(0.548)	(0.543)
Study group (c.f. Already User (T1))			
Prospective user (T2)	0.073***	3.437	0.435*
	(0.046)	(2.720)	(0.151)
Control group (C)	0.101	8.884*	0.744
	(0.130)	(7.662)	(0.301)
Solar ownership at baseline			
SHS owned at baseline (number)	0.053**		
	(0.053)		
Panels owned at baseline (number)		0.595	
		(0.165)	
Solar devices of either type owned at baseline (number)			0.390*
			(0.146)
cut1	-2.003	-4.116	-3.440*
	(4.087)	(2.224)	(1.427)
cut2	5.261	-1.015	0.148
	(4.616)	(2.197)	(1.457)
Observations	145	209	332
AIC	154.791	384.621	574.576
BIC	214.326	461.495	662.094

Exponentiated coefficients; Standard errors clustered by village in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$