Bringing Power to the People of Uganda: Determinants of solar Photovoltaics adoption in Uganda

Abstract

We examine the factors determining the adoption and use of solar photovoltaics (PV) technologies in Uganda using the detailed Uganda 2018/2019 Living Standards Measurement Survey (LSMS) household data. The aim is to promote a modern energy source like solar energy that increases accessibility, reliability, and affordability of electricity, thus achieving the goal of clean energy for all in Uganda. Data was analyzed with a Probit model and a Multivariate Probit model. It is found that the major drivers of solar PVs use in Uganda are saving, wealth, education, age of household head and household size. However, households in urban areas, households with access to grid-electricity, households with reliable grid-electricity supply and male-headed households are less likely to adopt solar PVs. The study recommends that, the government should promote awareness on solar energy and establish credit schemes for solar provision to lessen the burden of upfront investment in solar, making it relatively affordable.

Keywords: Multivariate Probit, Renewable energy, Lighting

1. Introduction

Electricity is critical to the welfare of households, and it is important in the development process (Beenstock et al., 1999; Ucan et al., 2014). The benefits of electricity include improved household welfare, economic development, prevention of environmental degradation (since the biggest percentage is hydro and solar), and protection of human health through prevention of indoor pollution. For these reasons, the Sustainable Development Goals (SDGs) focus on ensuring access to affordable, reliable, sustainable, and modern energy for all by 2030. Even though Uganda has implemented several programs to increase electricity generating capacity and expand the electricity grid to the rural areas, e.g., Uganda's Rural Electrification Project (REP), the country still has most of its population not connected to the electricity grid. Only

15% of the households accessed electricity through the grid (National or mini-grid) in 2019, most of which lived in urban areas (UBOS, 2019)

Additionally, in Uganda, like many African countries, many households find electricity costly, both in terms of connection fees and price of electricity (Blimpo & Cosgrove-Davies, 2019). The current monthly household electricity tariffs in Uganda, in addition to monthly service charges of UGX 3360 (US$0.95), are UGX250/kWh (US0.07/kWh) for the first 15 kWh and UGX747.5/kWh (US0.21/kWh) thereafter (ERA, 2021). These charges are too high for most households in Uganda. There are also critical constraints related to electricity transmission (grid). Therefore, due to insufficient or lack of grid accessibility, many households, firms, and public agencies that would otherwise use electricity do not have access to supplies through the grid. Moreover, grid extension and maintenance are costly. In addition to that, the areas without grid access are usually characterized by widely dispersed households in remote communities, making it more costly to provide grid electricity to most of these areas.

However, off-grid solar energy has become a viable alternative (or supplement) to utility-supplied electricity systems in villages and towns across Uganda. Off-grid solar power is expanding rapidly, and the LSMS 2018/2019 reports that 36% of the households surveyed, used solar energy for lighting. Even households that have access to the grid might find it desirable to install solar PV as an alternative or supplement to electricity from the grid since the supply from the grid is unreliable, characterized with frequent blackouts – both planned and unplanned. A few households have diesel (gasoline) generators as a backup in case of power failure but for most households, solar PV units may be a cheaper alternative. Fortunately, Uganda is well endowed with abundant sunshine hours and solar radiation, therefore, unlike grid electricity, the risks of electricity blackouts from solar electricity are not likely. There are small variations in radiation and electricity demand through the year, so there is less need for long term electricity storage than in places with larger seasonal variations.

Electricity from the grid requires that households purchase grid connection, and pay monthly service charges and energy charges, while for solar energy use, the costs usually relate to the purchase of the solar kit (equipment), while there are no recurring (variable) costs. Electricity connection also requires a modern roof, yet many people in Uganda have houses that do not comply with the required standards that 230 Volt electricity can be safely installed (Blimpo & Cosgrove-Davies, 2019). Most small solar systems run on 12Volts and therefore have fewer requirements for house quality, and they do not require a modern roof for installation.

However, the most important question that concerns access to electricity is: what are the major drivers to the adoption and use of solar PVs in Uganda? Therefore, this study aims at assessing and empirically examining the factors that determine the use of solar PV technologies in Uganda by employing binary probit and Multivariate probit models.

We aim at exploring ways to increase electrification among Ugandans by encouraging adoption of the decentralized solar energy as a supplement to grid and alternative for sparsely populated areas where establishing grid would be very costly. This is hoped to solve the energy poverty problem in Uganda. The paper will, therefore, contribute to the debate on energy poverty in Uganda. I.e., by identifying the modern energy source that increases accessibility, reliability and affordability of electricity thus achieving the goal of clean energy for all in Uganda.

This study brings forth new evidence by utilizing the detailed Uganda 2018/2019 Living Standards Measurement Survey (LSMS) household data to analyze the household energy demand in the country. This study is specific to Uganda to identify its uniqueness in terms of the drivers of solar PV adoption.

The remainder of the paper is organized as follows: Section 2 reviews the relevant literature. Section 3 presents the research methodology. Section 4 offers the empirical results, while Section 5 provides the conclusion and recommendations.

2. Literature Review

More than 1.5 billion people worldwide lack access to electricity (Hassan and Lucchnino, 2011). The situation is also bad in Uganda. According to National Electrification Survey by UBOS in 2018, only 28% of the Ugandan population had access to electricity (Aarakit, Sylvia M et al., 2021). Their results suggested that supply-side gaps constituted the biggest proportion of electricity access deficit in Uganda’s households. The supply side gap due to grid constraints allows exploiting other sources of energy in Uganda, particularly solar PV systems. Accordingly, Avellino (2018) contends that solar energy is increasingly vital due to its reliability and cost-effectiveness. Besides, the supply of sunshine in Uganda gives a high potential for solar energy production. About 200,000 km^2 of Uganda's land area has solar radiation exceeding 2,000 kWh/m^2 /year (Avellino et al., 2018). In addition, (Buragohain, 2012; Peters, 2020; Urmee & Harries, 2011; Wijayatunga & Attalage, 2005) assert that off-grid solar solutions have played a key role in extending energy access to millions of people, especially in sub-Saharan African and South Asia. off-grid solar sector has grown rapidly over the past decade (Peters, 2020). Moreover, UBOS (2018) found that, although the willingness to pay for electricity services was high among the unserved, many respondents pointed out that electricity unreliability was a big challenge; consequently, solar PV adoption is growing in Uganda.

There are several drivers for the increased adoption of solar PV systems. (Aarakit, Sylvia Manjeri et al., 2021; Buragohain, 2012; Ondraczek, 2013; Urmee & Harries, 2011; Wijayatunga & Attalage, 2005) pointed out that availability, affordability, financial initiatives, and awareness through aggressive marketing strategies as being the critical factors for solar PV adoption. For example, (Ondraczek, 2013), in his study on the status of solar markets in Kenya and Tanzania, found that awareness, availability, and affordability are significant drivers of the rapid adoption of off-grid solar technologies in emerging markets. He explains that solar is affordable due to escalating tariffs and scarcity of conventional hydro and thermal generated electricity in these countries. In most developing countries, even when there is access to electricity, households and business units face the challenge of irregular electricity supply. The privatization of the energy sector in these countries also contributed to high prices of hydroelectricity (Ondraczek, 2013). Therefore, solar PV poses an alternative option to those where the supply is irregular or not served at all by hydroelectricity, such as in rural areas; besides, solar PV is more affordable.

Additionally, (Aarakit, Sylvia Manjeri et al., 2021), found that the drop in global prices for solar PV systems, inadequate electricity infrastructure (transmission and distribution), commitment and awareness campaigns from the government and development institutions (World Bank, DFID, GTZ, UNCDF and USAID), innovations from the solar industry and increased power outage as significant drives of the adoption of the solar PV system. Besides, there tax subsidies for some solar PV systems and components making solar PVs make more affordable, thus increasing solar PV uptake in Uganda (Aarakit, Sylvia Manjeri et al., 2021).

However, there are challenges associated with solar PV system adoption. According to Avellino (2018), in Uganda, energy rules and regulations cut across all the energy power generation industries and are not adequately implemented. Similarly, (Urmee & Harries, 2011) contend that the lack of a national renewable energy policy supporting renewable rural electrification was a constraint to the successful adoption of solar PVs in Bangladesh. In

Uganda, (Avellino et al., 2018) finds that there were no subsidies to encourage higher investment in solar energy. Most solar energy consumers depend on small scale photovoltaic plants for domestic use. However, with the construction of the Soroti 10MW solar power station in 2016, the Tororo 10MW solar power station in 2017, Kabulasoke 20MW solar power station in 2019 and Mayuge 10MW solar power station in 2019 and Tororo PV Ltd 10 MW, is hoped to increase the use of solar energy on industrial scale. These solar power stations were privately funded.

Also, (Mondal & Klein, 2011; Urmee & Harries, 2011; Wassie & Adaramola, 2021) point out that poor quality and counterfeit solar products in the market, high cost of quality-verified solar products, lack of after-sales maintenance services, limited access to credit finance to acquire quality-verified solar products and lack of adequate knowledge and operational skills (low awareness of solar PV systems) are hindering successful solar PV adoption.

(Wassie & Adaramola, 2021) found that solar electrified grocery owners in Rema village in northwest Ethiopia realized improved income levels. Similarly, (Obeng & Evers, 2010), in their study in rural Ghana, found that there was additional income after sunset of US$5-12/day in solar electrified grocery enterprises. Also, (Urmee & Harries, 2011) reported that after solar PV adoption in rural Bangladesh, there were opportunities for starting up new businesses, and businesses could remain open after dusk to earn extra income from late shoppers. The increased income level may be due to more time spent on income-generating activities by solar PV beneficiaries.

Besides that, (Buragohain, 2012; Mondal & Klein, 2011; Urmee & Harries, 2011) found that households experienced improved quality of life and social status and better quality of light after adopting Solar PVs. Moreover, there was a reduction in expenditure on lighting after solar adoption (Buragohain, 2012; Obeng & Evers, 2010; Wassie & Adaramola, 2021). For instance, (Obeng & Evers, 2010) found that in rural Ghana, solar PV lighting instead of kerosene reduces energy costs by US$1-5/month. Similarly, (Wassie & Adaramola, 2021) estimated a US$65-75/year by rural households in Ethiopia if they use solar PVs instead of kerosene. Additionally, regarding environmental effects, solar electrification could save 43.68 litres of kerosene consumption and emissions of 107 kg CO_2 per year in rural Ethiopia (Wassie & Adaramola, 2021). Using solar PVs instead of kerosene lamps reduces air pollution, hence less health damage (Buragohain, 2012; Mondal & Klein, 2011; Wijayatunga & Attalage, 2005).

Solar lighting is a relevant and practical input in education since children can study for more extended hours (Buragohain, 2012; Hassan & Lucchino, 2016; Mondal & Klein, 2011; Wijayatunga & Attalage, 2005). (Buragohain, 2012) found that 53-69% of the respondents in his study reported better education quality. Furthermore, solar electrification of health centers and schools provides safer child delivery and improved quality of education (Wassie & Adaramola, 2021). Moreover, (Buragohain, 2012) noted that after solar street lighting in Indian rural villages, the crime rate reduced.

Given the grid electricity failure to close the energy poverty gap, and the socioeconomic and environmental benefits of solar energy, it's worth exploring the determinants of solar PV adoption in Uganda…There is extensive research on the role of solar PV systems in fulfilling the basic electricity needs and improving the health, education, and welfare of rural households and the reasons for its adoption in many developing countries. However, there is an inadequate examination of the determinants of solar PV adoption in Uganda. Therefore, this paper aims at filling this research gap.

Although Aarakit et al. (2021) studied the adoption of solar photovoltaic systems in households in Uganda, their study uses a different data set from our paper. They used the 2018 National Electrification Survey data set whereas we employed the 2018/2019 Living Standards Measure Survey (LSMS) household data to analyze the household solar energy adoption in the country. Do these different data sets produce similar results? Importantly, Aarakit et al. (2021) employed a different research methodology (Conditional Mixed Process (CMP) model) in our study we employed different research methods specifically the Binary Probit and Multivariate Probit Models. The Multivariate Probit model is the most appropriate model for analyzing solar PVs adoption since we believe that solar PV adoption is correlated with grid electricity, the use of kerosene and other lighting forms. The study by Aarakit et al. (2021) does not consider other lighting energy sources in their model yet solar adoption is highly correlated with these energy sources hence need to be jointly estimated in a multivariate model. Also, our study differs from Aarakit et al. (2021) by focusing on many possible determinants (wealth, saving, education, location, household size, grid-electricity prices, reliability grid-electricity supply, gender, age, grid-connection) of solar adoption in Uganda. Aarakit (2021) emphasizes flexible payment mechanisms (affordability) and influential persons (social factors) as the determinants of solar adoption in Uganda.

3. Research Methodology

3.1 Model Specification and Econometric Methodology

Two econometric analyses were carried out (i)using binary probit regression (binary probit) and (ii) multivariate probit (MVP) models to analyze the major factors that are influencing the adoption and purchase of solar PVs in Uganda. Binary probit regression models are used to examine the relationship between a binary dependent variable y and one or more explanatory variables X. The dependent variable ' y ' in this study represents the household's decision to purchase and use solar PV. (y = 1, adopt; y = 0, otherwise), Meanwhile, the explanatory variables can take any form (discrete, continuous).

The binary regression is mathematically specified as:

$$y_i^* = X\beta + \epsilon \qquad (1)$$

$$y_i = \begin{cases} 1 & \text{if} \quad y_i^* > 0 \\ 0 & \text{if} \quad y_i^* \leq 0 \end{cases} \qquad (2)$$

Where y_i^* is a latent (unobserved) variable, y_i is the observed variable that takes on the value of 1 if a household i has a solar panel and zero otherwise. X is a vector of independent variables.

We also employ a multivariate probit model to examine the major determinants of the adoption of solar PVs in Uganda. Multivariate probit models are used to estimate more than one correlated binary dependent variables jointly. This model is the most appropriate model for analyzing solar PVs adoption since we believe that solar PV adoption is correlated with grid electricity, the use of kerosene and other lighting forms. Therefore, we estimate Multivariate Probit model analysis with four binary outcome choice variables namely: solar PVs, grid-electricity, kerosene, and others (none of the mentioned three). The multivariate probit model has also been used by (Ali et al., 2019; Behera et al., 2015; Wassie & Adaramola, 2021) to analyze the determinants of household choices of alternative energy sources for lighting. Following (Mullahy, 2016), the multivariate probit model in this paper was formulated as:

$$y_{ij}^* = X_i\beta_j + u_{ij} \qquad (3)$$

$$y_{ij} = \begin{cases} 1 & \text{if} \quad y_{ij}^* > 0 \\ 0 & \text{if} \quad y_{ij}^* \leq 0 \end{cases} \qquad (4)$$

In this model, y represents the four binary outcomes (lighting fuel choices), namely: Solar PVs, grid-electricity, kerosene, and others. For each type of lighting fuel choice, the household is faced with a binary choice (1 = use of the energy type, or 0 = otherwise).

$i = 1,2,3 \ldots N$ indexes observations, $j = 1,2,3,4$ index outcome

where X is a matrix of the explanatory variables; $\beta_1, \beta_2, \beta_3 and \beta_4$ are parameter estimates and u_{ij} are assumed to be independent identically distributed across i but correlated across j for any i. The model is estimated using the maximum likelihood estimation.

3.2 Data

We use the LSMS data for 2018/2019 Uganda. The data collected from the household survey included demographic and socioeconomic characteristics and energy sources. It has information on households that are grid-electrified, solar electrified, kerosene lighting and other lighting fuels.

The study uses a Multivariate Probit (MVP) Model, four outcome choice variables ((1) solar PVs, (2) grid-electricity (3) kerosene and (4) others) were included in the model. The dependent variables (the choice to adopt a given energy source) are binary outcomes that take on the values of 1= adopt and 0= otherwise.

The decision to adopt solar electrification depends on many factors, both economic and non-economic factors. Therefore, the determinants on solar PV adoption may include;

1. Wealth. This is measured as household total wealth which includes income and valuable possessions. Wealth can be negative if a person has debts. A positive coefficient is expected since wealth increases household purchasing power, leading to higher demand for solar PV systems. Also (Guta, 2018) argues that solar energy production is a luxury good, especially in low-income countries. Therefore, its adoption is likely to increase with wealth. Besides, (Smith & Urpelainen, 2014) found a positive effect of wealth on solar adoption in East African countries.
2. Saving. This dummy variable takes 1 for having saved and 0 for no saving. A positive coefficient is expected since saving increases the ability to cover the up-front investment for solar PV systems.

3. Education. This refers to the education level of the household head. It is measured as the number of years of completed schooling. We expect a positive coefficient because, with higher education, there is greater awareness of the uses and benefits of solar PV systems. Also (Guta, 2018) argues that education improves employment opportunities. This increases household income, thus affordability of solar PVS.
4. Gender of the household head. It's a dummy variable that takes on 1 for males and 0 otherwise. Here a negative coefficient is expected. This is because, in most developing countries, females are responsible for laborious energy acquisition (Guta, 2018). Since women are more affected by lack of energy, they are more willing to pay for renewable energy technologies like solar PV than their male counterparts. On the other hand, male-headed households could be richer hence affording grid electricity.
5. Age of the household head. The coefficient can be positive or negative. Since young people are more aware of the environmental benefits of renewable energy technologies, they may be willing to for solar PVS. Thus indication a negative coefficient of age (Guta, 2018). However, this author also argues that the older may be wealthier and more likely to invest in solar technologies. Thus, a positive coefficient is expected.
6. Location of the household. This dummy variable takes on 1 if the household is in urban areas and 0 if the household is in rural areas. A positive coefficient is expected. According to the findings of (Lewis & Pattanayak, 2012), urban areas are positively associated with the adoption of cleaner fuels than those in rural locations. Therefore, we expect the adoption of solar PV systems to be high in urban areas than rural ones. Besides, urban households are likely to be close to the source.
7. Household size. This may have a positive or negative effect on solar adoption. If the household size is large, the adoption of solar PV is most likely to be high since they are large consumers of energy and can spread the fixed cost over the household members (Guta, 2018). Therefore, a positive effect is expected. However, (Guta, 2018) argues that household size increases expenditure on various commodities, leaving few resources for solar adoption. In this case, a negative impact is expected.
8. Electricity prices. It is measured as the electricity price per kWh. This may positively affect the adoption of solar PVs; hence a positive coefficient is expected. Since grid-electricity and solar energy are potential substitutes, an increase in grid-electricity prices may indicate a higher probability for solar PVs adoption. Moreover, (Ondraczek, 2013), in their study in Kenya and Tanzania, recognizes that escalating hydroelectricity tariffs make solar energy more affordable, thereby driving the uptake of solar PVs.

9. Reliability of grid-electricity supply. Here the study uses average electricity hours per day as a proxy for the reliability of grid-electricity supply. A negative coefficient is expected since where the supply of grid-electricity is regular (longer hours of grid-electricity supply), the likelihood of adopting solar PVs diminishes. However, in the case of irregular grid-electricity supply, solar PVs are viewed as an alternative option, thereby increasing the probability of up taking solar PVs (Aarakit, Sylvia Manjeri et al., 2021; Ondraczek, 2013).
10. Grid connection. This is a dummy variable that takes on 1 if connected and 0 otherwise. A negative coefficient is expected since households already connected to the grid may perceive solar adoption as an additional expenditure. They may also perceive solar PV as having a low-level use (Guta, 2018). Thus, there may be a lock-in effect.

4. Results and Discussion

4.1 Descriptive Statistics

Table 1: Summary Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Solar use	3155	.361	.48	0	1
Grid	3170	.38	.486	0	1
Location	3170	.255	.436	0	1
Elec price	3170	690.272	78.717	572.4	771.1
Age hhhead	3170	47.373	15.728	18	98
Hhsize	3170	5.668	2.992	1	22
Gender	3170	.346	.476	0	1
Elec hrs	3170	3.076	7.666	0	24
Saving	3128	.845	.362	0	1
Wealth	3080	10328293	3.377e+08	-4.300e+08	1.872e+10
Educ level	2950	5.957	4.481	0	16

Note: Grid is a dummy variable taking on 1 for access to grid-electricity and 0 for no access, elec_price is average electricity prices per KWH, age_hhhead is the age of the household head, Hhsize is the size of the household, elec_hrs is average electricity hours per day, and edu_level is the years of completed schooling of the household head, location is a dummy variable taking on 1 for urban location and 0 for rural location, gender is a dummy variable taking on 1 for male and 0 for female and Saving is a dummy variable taking on 1 for if household saved and 0 if household.

Table 1 reports the summary statistics of all the variables used in this study. Only a few (36%) households used solar PVs while 38% of the respondents had access to grid-electricity. Regarding location, only 25.5 % of the households are in urban areas. This implies that most Ugandans live in rural areas. The average price of electricity per unit was 690 Uganda shillings. The average age of the household was 47 years. The household size was 6 members on average. Regarding gender, only 34.6% were male-headed households. Looking at the number of hours electricity is available; the average electricity hours was 3 hours per day. This implies electricity is unreliable and is characterized by blackouts in Uganda. on average, 84.4% of the respondents saved money. The respondents had, on average approximately 6 years of completed schooling. The average annual wealth of the surveyed households is UGX 10,328,000 which is approximately USD 2,856.

4.2 Determinants of Solar PVs Adoption in Uganda

Table 2: Correlation Matrix

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(1) solar_use	1.000										
(2) grid	-0.170	1.000									
(3) urban	-0.181	0.486	1.000								
(4) wealth	0.028	-0.010	0.037	1.000							
(5) elec_pric	-0.036	0.151	0.099	0.008	1.000						
(6) age_hhd	0.014	-0.026	-0.029	-0.006	0.030	1.000					
(7) hhsize	0.151	-0.079	-0.073	0.026	0.064	0.050	1.000				
(8) gender	-0.119	0.037	0.008	0.024	0.014	0.152	-0.158	1.000			
(9) elec_hrs	-0.256	0.498	0.478	-0.003	0.187	-0.044	-0.052	0.015	1.000		
(10) saving	0.097	0.049	0.052	0.011	-0.039	-0.107	0.042	-0.056	0.043	1.000	
(11) educ_level	0.054	0.237	0.248	0.043	0.092	-0.247	0.036	-0.274	0.289	0.133	1.000

Note: Grid is a dummy variable taking on 1 for access to grid-electricity and 0 for no access, elec_price is average electricity prices per kWh, age_hhhead is the age of the household head, Hhsize is the size of the household, elec_hrs is average electricity hours per day, and edu_level is the years of completed schooling of the household head, location is a dummy variable taking on 1 for urban location and 0 for rural location, gender is a dummy variable taking on 1 for male and 0 for female and Saving is a dummy variable taking on 1 for if household saved and 0 if household.

We begin by analyzing the correlation matrix between variables, as presented in Table 2. The correlation coefficients measure whether and how strongly solar PV adoption is related to the explanatory variables. The correlation coefficient between solar use and access to grid-electricity is negative as expected, suggesting the two energy fuels are substitutes. Additionally, it suggests that households connected to the grid may be reluctant to adopt solar PVs. Also, being in urban area, electricity prices, being male-headed household and electricity hours are negatively associated with the adoption of solar PVs. Whereas wealth, age, household size, saving and education are positively correlated with the adoption of solar PVs.

Next, we examine the determinants of solar PVs adoption by applying two econometric analysis models, binary probit and multivariate probit (MVP). Table 3 reports the results on the determinants of solar adoption in Uganda from the probit model. The study uses the estimated marginal effects in the analysis for better interpretation.

Table 3: Determinants of Solar PVs Adoption in Uganda – probit regressions – Full Sample

VARIABLES	(1) dy/dx	(2) dy/dx	(3) dy/dx
Grid	-0.10	-0.18***	
	(0.06)	(0.06)	
Location	-0.29***		-0.33***
	(0.07)		(0.07)
elec_price	3.0e-5	1.0e-5	1.0e-5
	(1.0e-4)	(1.0e-4)	(1.0e-4)
age_hhd	1.4e-3**	1.4e-3**	1.4e-3**
	(5.6e-4)	(5.6e-4)	(5.6e-4)
Hhsize	0.05***	0.05***	0.05***
	(0.01)	(0.01)	(0.01)
Gender	-0.18***	-0.18***	-0.19***
	(0.06)	(0.06)	(0.06)
elec_hrs	-0.07***	-0.08***	-0.08***
	(0.01)	(0.01)	(0.01)
Saving	0.37***	0.36***	0.37***
	(0.07)	(0.07)	(0.07)
educ_level	0.04***	0.04***	0.04***
	(0.01)	(0.01)	(0.01)
Wealth	2.6e-9***	2.7e-9***	2.7e-9***
	(7.8e-10)	(7.8e-10)	(7.8e-10)
Constant	-1.19***	-1.21***	-1.18***
	(0.25)	(0.25)	(0.25)
Observations	2,818	2,818	2,818

Note: dy/dx refers to marginal effects from the probit regression. Figures in parentheses are Robust standard errors, ****, **, * stand for statistical significance at 1 percent, 5 percent, and 10 percent levels, respectively. Grid is a dummy variable taking on 1 for access to grid-electricity and 0 for no access, elec_price is average electricity prices per KWH, age_hhhead is the age of the household head, Hhsize is the size of the household, elec_hrs is average electricity hours per day, and edu_level is the years of completed schooling of the household head, location is a dummy variable taking on 1 for urban location and 0 for rural location, gender is a dummy variable taking on 1 for male and 0 for female and Saving is a dummy variable taking on 1 for if household saved and 0 if household.

As evidenced in model 1 in Table 3, location negatively affects solar adoption in Uganda. Being in an urban area reduces the probability of adopting solar PVs by 29%, and the variable is statistically significant at 1% level of significance. The marginal effect becomes larger in model 3 after dropping the access to grid variable. We omit access to the grid to avoid multicollinearity since grid access and location are highly correlated. The negative marginal effect of the location variable implies households in urban areas are less likely to adopt solar PVs than their rural counterparts. The argument may be that urban households in Uganda are already connected to grid-electricity, hence perceiving solar adoption as an additional expenditure. They may also perceive solar PV as having a low-level use and grid electricity as a better-quality energy source. Our results contradict (Lewis & Pattanayak, 2012), who claims that urban areas are positively associated with the adoption of cleaner fuels than those in rural locations unless the reason of not adopting is that they are already connected to the grid.

Even if, (Aarakit, Sylvia M et al., 2021; Giri & Goswami, 2017; Wassie & Adaramola, 2021) found that access to grid-electricity significantly and negatively influenced solar PVs adoption, this variable is insignificant in model 1 though rightly signed. Estimating a model including both access to grid electricity and location of the household may (since the variables are highly correlated) suffer multicollinearity problems. Multicollinearity leads to large standard errors, thus making the access to grid-electricity variable insignificant in the model. If we omit the location variable, access to the grid-electricity variable becomes statistically significant at 1% level of significance, as seen in model 2. Having access to grid-electricity reduces the probability of adopting solar PVs by 18%. This may imply that those already connected to the grid may be reluctant to adopt solar PVs because they may perceive solar adoption as an additional cost, and there may be a lock-in effect to grid-electricity.

being a male-headed household reduces the probability of adopting solar PVs by 20%, and the variable is statistically significant at 1% level of significance. This implies a higher likelihood for a female-headed household to adopt solar PVs than the male-headed ones. (Guta, 2018) found that male-headed households are less likely to adopt solar PVs than female-headed counterparts. This confirms our earlier argument in subsection 3.2 that since women in Africa are more responsible for energy collection, they are more affected by lack of energy hence may be more willing to pay for cleaner and convenient energy technologies like solar PVs. Moreover, male tend to be wealthier than women and may have already connected to the grid. (Wassie & Adaramola, 2021) found the gender of household heads insignificant in their study in rural Ethiopia.

Considering electricity hours, which is a proxy for the reliability of grid-electricity supply, a unit increase in grid-electricity hours reduces solar PVs adoption by 7%, and it's statistically significant at 1% level of significance. This implies that where grid-electricity supply is reliable, the probability of adopting solar PVs falls. This may also indicate that once the grid-electricity is reliable, it is preferred to solar energy. Also, (Aarakit, Sylvia Manjeri et al., 2021) point out that increased grid-electricity outage significantly drives solar PVs uptake.

we find that an increase in wealth increases the probability of solar PV adoption. The variable is positive and statistically significant at 1% level of significance. Similar results are reported by (Guta, 2018; Urpelainen, 2014; Wassie & Adaramola, 2021), who found that wealthier households have a higher probability of investing in solar PVs than poor ones. However, the marginal effect of wealth on solar adoption is very small. We argue that wealthier households are mainly located in urban areas and already have access grid-electricity. Hence, they may perceive solar adoption as an additional cost and there may be a lock-in effect, thereby causing a minimal effect of wealth on solar adoption. Also, (Giri & Goswami, 2017) found that households are less likely to use solar energy relative to electricity with an increase in income since electricity is a better quality energy source.

Focusing on saving, a percentage increase in savings increases the probability of adopting solar PVs by 37%. This may be because with increased savings households can afford to cover the up-front investment of solar PVs.

Concerning household size, the study finds that a unit increase in the household size increases the probability of solar adoption by 5%. The variable is positive and statistically significant at 1% level of significance. Likewise, (Giri & Goswami, 2017; Guta, 2018) found that the household size affects solar PVs' adoption positively. This may be because the fixed cost of solar PVs can be spread among the household members. On the contrary, (Wassie & Adaramola, 2021) found a negative effect of household size on solar PVs adoption, and they argued that a large house size might mean more rooms to light; hence they may find solar expensive.

Considering the education level of the household head, the marginal effect of this variable is positive and statistically significant at 1% level of significance. An increase in the household head level of education by 1 year increases the probability of up taking solar energy by 4%. Similar results are reported by (Giri & Goswami, 2017; Guta, 2018), who argue education increases purchasing power and awareness hence the preference for cleaner and convenient energy sources like solar.

Like (Guta, 2018), this study found the age of the household head as a positive determinant of solar PVs adoption. This implies that older household heads may be richer and thus can afford to adopt solar PVs. However, age has minimal effect on solar adoption, as indicated by the very small marginal effects in all the models. Besides, (Wassie & Adaramola, 2021) found that the age of the household head does not influence solar PVs adoption.

Also, Electricity prices do not influence the decision to adopt solar PVs in Uganda since these variables are insignificant, as shown in all the models in Table 3.

we carried out robustness checks to examine the sensitivity of our results described in Table 3 and these findings are reported in table 4 below. The robustness check involved diving the full sample into two sub-samples namely, urban households and rural households sub-samples. This was done to check if our results are not affected by the location of the households given that urban households and rural households in Uganda exhibit different characteristics hence factors affecting solar adoption may defer by location.

Table4: Determinants of Solar PVs Adoption in Uganda – probit regressions, using urban and rural Sub-samples.

	(1) Urban sub-sample	(2) Rural sub-sample
VARIABLES	dy/dx	dy/dx
Grid	-0.11	-0.12*
	(0.15)	(0.07)
elec_pric	5.0e-5	4.0e-5
	(1.9e-4)	(1e-4)
age_hhd	0.001	1.5e-3**
	(0.001)	(6.7e-4)
Hhsize	0.06***	0.04***
	(0.02)	(0.01)
Gender	-0.13	-0.18***
	(0.14)	(0.06)
elec_hrs	-0.08***	-0.07***
	(0.01)	(0.01)
Saving	0.58***	0.33***
	(0.21)	(0.08)
educ_level	0.03**	0.04***
	(0.01)	(0.01)
Wealth	3.8e-11	9.7e-9***
	(1.3e-10)	(1.9e-9)
Constant	-1.79***	-1.20***
	(0.68)	(0.27)
Observations	680	2,138

Note: dy/dx refers to marginal effects from the probit regression. Figures in parentheses are Robust standard errors, ****, **, * stand for statistical significance at 1 percent, 5 percent, and 10 percent levels, respectively. Grid is a dummy variable taking on 1 for access to grid-electricity and 0 for no access, elec_price is average electricity prices per KWH, age_hhhead is the age of the household head, Hhsize is the size of the household, elec_hrs is average electricity hours per day, and edu_level is the years of completed schooling of the household head, location is a dummy variable taking on 1 for urban location and 0 for rural location, gender is a dummy variable taking on 1 for male and 0 for female and Saving is a dummy variable taking on 1 for if household saved and 0 if household.

Considering the urban households' sub-sample, the positive significant drivers of solar adoption are saving, education of the household head and household size. The results are similar to those reported in Table 3 above with exception of saving which now has a much bigger impact on solar adoption with the probability of 58%. The reliability of grid-electricity measured by electricity hours has a negative and significant marginal effect of 0.08 which increases slightly compared to the results reported in Table 3. Implying that reliable grid-electricity supply reduces the likelihood of adopting solar in urban Uganda. The electricity prices variable is still insignificant just like what was reported in Table 3. Sensitive to sample modification are the variables of gender, grid access, age and wealth which now are insignificant in the urban sub-sample. The weakening of the results in the urban sub-sample may be due to the differences in the characteristics of rural and urban households.

Considering the rural sub-sample, the results are very similar to those reported in Table 3 in terms of sign and significance. The magnitude of the coefficients changes slightly. Similar to Table3 results, savings, education of the household head, household size, age and wealth increase the probability of adopting solar. The marginal effect of wealth increases slightly in the rural sample. On the other hand, male-headed households, households with access to the electricity grid and households with reliable grid-electricity supply are less likely to adopt solar. Electricity prices do not statistically significantly affect solar adoption.

Table 5: Correlation Matrix for the various energy sources

Variables	(1)	(2)	(3)	(4)
(1) solar_use	1.000			
(2) grid-electricity	-0.6084*** (0.0374)	1.000		
(3) Kerosene_use	-0.5287*** (0.0283)	-0.1701*** (0.0476)	1.000	
(4) Others	-0.9985*** (0.0820)	-0.994*** (0.0293)	-0.9633*** (0.0315)	1.000

From Table 5 above we observe that the correlation coefficients between solar use and the three energy sources are high and negative as expected. They range from -0.5287 to -0.9985. The negative sign indicates that the energy sources are potential substitutes. The high correlation between the various energy sources with solar use suggests that the Multivariate probit model is the most appropriate model for analyzing solar PVs adoption. The model compares factors affecting the adoption of various energy sources, which is a valuable insight.

Subsequently, Table 6 reports the estimated multivariate probit coefficients.

Table 6: Determinants of Solar PVs Adoption in Uganda – Multivariate probit Model

VARIABLES	(1) Solar	(2) Grid-electricity	(3) Kerosene	(4) Others
Location	-0.6674***	1.4588***	-0.136**	-0.2341***
	(0.0662)	(0.0699)	(0.0640)	(0.0644)
educ_level	0.0219***	0.0840***	-0.0044	-0.0599***
	(0.0061)	(0.0084)	(0.0063)	(0.0067)
age_hhd	0.0038**	-0.0012	0.0033**	-0.0064***
	(0.0016)	(0.0022)	(0.0017)	(0.0017)
Hhsize	0.0492***	-0.0093	-0.0121	-0.0258***
	(0.0083)	(0.0122)	(0.0089)	(0.0089)
Gender	-0.2290***	0.2600***	0.0805	-0.0576
	(0.0560)	(0.0753)	(0.0567)	(0.0551)
Saving	0.3621***	0.082	0.0187	-0.3301***
	(0.0709)	(0.1058)	(0.0717)	(0.0669)
Wealth	0.0000	0.0000	0.0000	0.0000
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Constant	-1.0551***	-2.2700***	-0.7140***	0.6133***
	(0.1205)	(0.1879)	(0.1274)	(0.1241)
Observations	2,898	2,898	2,898	2,898

Figures in parentheses stand for Robust standard errors, ****, **, * stand for statistical significance at 1 percent, 5 percent, and 10 percent levels, respectively. age_hhd is the age of the household head, Hhsize is the size of the household, and edu_level is the years of completed schooling of the household head. Saving is a proxy for wealth.

the coefficients for location are negative and significant for solar, kerosene and others and positive for grid-electricity. This implies that urban households are more likely to adopt grid-electricity relative to other energy sources. This is because the grid is already in place hence access to grid-electricity moreover, this kind of electricity is viewed as a better energy source. Access to grid-electricity there is generally better in urban areas than in rural areas.

Meanwhile, the education level of the household head is positively associated with the adoption of solar and grid-electricity) and negative for other energy sources. This suggests that higher levels of education may lead to increased purchasing power and awareness; hence such households will prefer cleaner and more efficient energy sources. Further, household size increases the likelihood of using solar energy, decreasing the probability of using other energy sources but does not significantly affect the use of grid-electricity and kerosene. As expected, saving increases the probability of adopting solar PVs. We observe that savings reduces the likelihood of using other energy sources. This implies with increased savings households find the up-front investment in solar affordable besides being a clean energy source.

Regarding the age of the household head, age increases the probability of adopting solar and reduces the likelihood of using other energy sources. This may indicate that older people are wealthier thus can afford clean energy like solar. However, the age of the household head also increases the probability of using kerosene. The reasoning here is that older people are accustomed to using kerosene hence a lock-in effect, and they may lack awareness of modern energy technologies like solar and grid-electricity. Concerning the gender of the household head, being a male-headed household reduces the probability of adopting solar but increases the likelihood of using grid-electricity. We argue that women may prefer solar energy clean energy relative to kerosene, and it's more affordable than grid-electricity. While males may choose grid-electricity since they can afford it, given that, on average, males are richer than females in Uganda. Focusing on wealth, though rightly singed (positive coefficient) its marginal effect on all energy sources is very minimal.

5. Conclusions and recommendations

The goal of this study was to empirically examine the factors affecting solar PVs adoption in Uganda. The findings from the probit and multivariate probit are that the uptake of solar PVs in Uganda is driven by savings, education, age of the household head, size of the household and wealth. Nevertheless, households in urban areas, households with access to grid-electricity, households with reliable grid-electricity supply and male-headed households are less likely to adopt solar PVs. Considering the various energy sources, households in urban areas prefer grid-electricity to solar, kerosene and other energy sources. This may imply that grid-electricity is of better quality e.g., in terms of voltage compared to other energy sources. Also, Solar PV units can be costly to buy, whereas with grid there may be less of an up-front investment, but you pay monthly. For liquidity constrained households the difference in cost profile over time might be decisive.

This paper provides the following recommendations. Firstly, given that most households in Uganda live below and around the poverty line, they have limited ability to pay for solar panels since the entire investment is up-front , at least in most cases. More research is needed through market innovation of various solar panels for further large cost reduction for the end-user. The government should establish credit schemes for solar provision to lessen the burden of upfront investment in solar, making it relatively affordable. The government should also educate people, especially rural household on the uses and benefits of clean solar energy. Education creates awareness on clean energy such as solar energy thus increasing its adopt solar. Thus, the government, developmental institutions and solar PVs dealers should undertake massive awareness campaigns for solar PVs adoption in Uganda. If possible, the government may enforce regulations on the quality PVs products and after-sales services provided by solar dealers. This is because the low-quality solar products and lack of after-sales services spoil the image of solar PVs, hence, hindering its adoption.

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Conflicts of interest:

We declare no conflict of interest.

Reference List

Aarakit, S. M., Ntayi, J. M., Wasswa, F., Adaramola, M. S. & Ssennono, V. F. (2021). Adoption of solar photovoltaic systems in households: Evidence from Uganda. *Journal of Cleaner Production*: 129619.

Aarakit, S. M., Ssennono, V. F. & Adaramola, M. S. (2021). Estimating Market Potential for Solar Photovoltaic Systems in Uganda. *FRONTIERS IN ENERGY RESEARCH*, 9.

Ali, A., Rahut, D. B., Mottaleb, K. A. & Aryal, J. P. (2019). Alternate energy sources for lighting among rural households in the Himalayan region of Pakistan: Access and impact. *Energy & Environment,* 30 (7): 1291-1312.

Avellino, O. W. K., Mwarania, F., Wahab, A.-H. A. & Aime, K. T. (2018). Uganda solar energy utilization: Current status and future trends. *Published in international journal of scientific and research publications,* 8 (3).

Beenstock, M., Goldin, E. & Nabot, D. (1999). The demand for electricity in Israel. *Energy Economics*, 21 (2): 168-183.

Behera, B., Jeetendra, A. & Ali, A. (2015). Household collection and use of biomass energy sources in South Asia. *Energy*, 85: 468-480.

Blimpo, M. P. & Cosgrove-Davies, M. (2019). *Electricity access in Sub-Saharan Africa: Uptake, reliability, and complementary factors for economic impact*: The World Bank.

Buragohain, T. (2012). Impact of solar energy in rural development in India. *International journal of environmental science and development,* 3 (4): 334.

Giri, M. & Goswami, B. (2017). Determinants of households' choice of energy for lighting in Nepal. *Economics and Business Letters*, 6 (2): 42-47.

Guta, D. D. (2018). Determinants of household adoption of solar energy technology in rural Ethiopia. *Journal of Cleaner Production*, 204: 193-204.

Hassan, F. & Lucchino, P. (2016). Powering education. *CEP Discussion Paper No 1438,* dp1438 (Centre for Economic Performance, LSE.).

Lewis, J. J. & Pattanayak, S. K. (2012). Who adopts improved fuels and cookstoves? A systematic review. *Environmental health perspectives*, 120 (5): 637-645.

Mondal, A. H. & Klein, D. (2011). Impacts of solar home systems on social development in rural Bangladesh. *Energy for Sustainable Development*, 15 (1): 17-20.

Mullahy, J. (2016). Estimation of multivariate probit models via bivariate probit. *The Stata Journal*, 16 (1): 37-51.

Obeng, G. Y. & Evers, H.-D. (2010). Impacts of public solar PV electrification on rural micro-enterprises: The case of Ghana. *Energy for Sustainable Development*, 14 (3): 223-231.

Ondraczek, J. (2013). The sun rises in the east (of Africa): A comparison of the development and status of solar energy markets in Kenya and Tanzania. *Energy Policy*, 56: 407-417.

Peters, D. R. R. S. K. (2020). *OFF-GRID SOLAR MARKET TRENDS REPORT 2020*.

Smith, M. G. & Urpelainen, J. (2014). Early Adopters of Solar Panels in Developing Countries: Evidence from T anzania. *Review of Policy Research*, 31 (1): 17-37.

UBOS. (2019). *Uganda Bureauof Statistics*. STATISTICAL ABSTRACT.

Ucan, O., Aricioglu, E. & Yucel, F. (2014). Energy consumption and economic growth nexus: Evidence from developed countries in Europe. *International Journal of Energy Economics and Policy*, 4 (3): 411.

Urmee, T. & Harries, D. (2011). Determinants of the success and sustainability of Bangladesh's SHS program. *Renewable Energy*, 36 (11): 2822-2830.

Urpelainen, J. (2014). Grid and off-grid electrification: An integrated model with applications to India. *Energy for Sustainable Development*, 19: 66-71.

Wassie, Y. T. & Adaramola, M. S. (2021). Socio-economic and environmental impacts of rural electrification with Solar Photovoltaic systems: Evidence from southern Ethiopia. *Energy for Sustainable Development*, 60: 52-66.

Wijayatunga, P. D. & Attalage, R. A. (2005). Socio-economic impact of solar home systems in rural Sri Lanka: a case-study. *Energy for Sustainable Development*, 9 (2): 5-9.