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Bringing Power to the People of Uganda: Determinants of Solar Photovoltaics Adoption in Uganda

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Abstract

This paper examines the factors determining the adoption and use of solar photovoltaic (PVs) technologies in Uganda using detailed Uganda 2018/2019 Living Standards Measurement Survey (LSMS) household data. The data were analyzed with a Probit model and a Multivariate Probit model. We found that the major drivers of solar PVs use in Uganda are: savings, income, 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 female-headed households are less likely to adopt solar PVs. The study recommends that the government should promote awareness of solar energy and establish credit schemes for solar provision to lessen the burden of upfront investment in solar.

Keywords

Multivariate Probit, Renewable Energy, Lighting, Solar Energy, Uganda

1. Introduction

Electricity is crucial to the welfare of households and is essential in the development process. Electricity provides lighting and power for electronic appliances, power tools, machines and more. Cooking with electricity reduces indoor pollution, which is a health hazard. Moving to the electricity generated from renewables is an important component of policies to reduce global warming. 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 Rural Electrification Project (REP), most of its population is 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).

Many households in Uganda find electricity too costly, both in terms of connection fees and the price of electricity (Blimpo & Cosgrove-Davies, 2019). In 2022, the monthly household electricity tariffs in Uganda, in addition to monthly service charges of UGX 3360 (US$0.95), was UGX250/kWh (US0.07/kWh) for the first 15 kWh and UGX747.5/kWh (US0.21/kWh) after that (Electricity Regulatory Authority [ERA], 2021). There are also critical constraints related to electricity transmission (grid). Due to the poorly developed grid, many households, firms, and public agencies that would otherwise use electricity cannot access supplies through the grid. Moreover, grid extension and maintenance are costly. The areas without grid access are usually characterized by widely dispersed households in remote communities, making providing grid electricity to most of these areas expensive.

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 report that 36% of the households surveyed used solar energy for lighting. Even households with access to the grid might find it desirable to install solar PV as a supplement to grid electricity because the supply from the grid is unreliable and characterized by 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 throughout the year. Therefore, unlike grid electricity, the risks of electricity blackouts from solar electricity are not likely. There are small variations in radiation and electricity demand throughout the year, so there is less need for long-term electricity storage than in places with larger seasonal variations.

Electricity from the grid requires households to purchase grid connections and pay monthly service and energy charges. In contrast, for solar energy use, the costs usually relate to purchasing the solar kit (equipment), while there are no recurring (variable) costs. Electricity connection also requires a modern roof (not grass-thatched) to safely install the required standard 230 Volt electricity. Yet, many houses in Uganda do not comply with this standard (Blimpo & Cosgrove-Davies, 2019). Fortunately, most small solar systems run on 12 Volts and therefore have fewer requirements for house quality and do not require a modern roof for installation.

However, the most important question that concerns access to electricity is: what are the major drivers of the adoption and use of solar PVs in Uganda? Therefore, this study aims to assess and empirically examine the factors that determine the use of solar PV technologies in Uganda. The Multivariate probit

(MVP) model is the best if the variables are highly correlated and there are possible substitutes. Therefore, in our analysis, we employ the MVP model.

We aim to explore ways to increase electrification among Ugandans by encouraging the adoption of decentralized solar energy to supplement the grid and as an alternative for sparsely populated areas where establishing a grid would be very costly. This paper is intended to contribute to the debate on energy poverty in Uganda by identifying constraints to the adoption of solar energy, thus contributing to the goal of clean and sustainable energy for all in Uganda by 2030 according to the SDGs.

This study brings forth new evidence on household energy demand in Uganda by using the detailed Uganda 2018/2019 Living Standards Measurement Survey (LSMS).

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 1.3 billion people worldwide lack access to electricity (Hassan & Lucchino, 2016). Access to electricity is also low in Uganda. According to the National Electrification Survey by UBOS in 2018, only 28% of the Ugandan population had access to electricity (Aarakit et al., 2021b). Their results suggested that supply-side gaps constituted the biggest proportion of the electricity access deficit in Ugandan households. The supply-side gap due to grid constraints can be ameliorated by using decentralized solar PV systems. The supply of sunshine in Uganda has a high potential for solar energy production. About 200,000 km^2 of Uganda's land area has solar radiation exceeding 2000 $kWh/m^2/year$ (Avellino et al., 2018). Off-grid solar solutions are playing an increasing role in extending energy access to millions of people, especially in sub-Saharan Africa and South Asia. The off-grid solar sector has grown rapidly over the past decade (Peters, 2020). The Uganda Bureau of Statistics (UBOS, 2018) found that, although the willingness to pay for electricity services was high among the unserved, many served respondents pointed out that electricity unreliability was a big challenge.

There are several drivers for the increased adoption of solar PV systems. Availability, affordability, financial incentives, and awareness through aggressive marketing strategies are critical for solar PV adoption (Wijayatunga & Attalage, 2005; Urmee & Harries, 2011; Buragohain, 2012; Ondraczek, 2013; Aarakit et al., 2021a). Ondraczek (2013) found that awareness, availability, and affordability are significant drivers of the rapid adoption of off-grid solar technologies in emerging markets. Ondraczek explains that solar is affordable due to escalating tariffs and the scarcity of conventional hydro and thermal-generated electricity in Kenya and Tanzania. However, in most developing countries, households and businesses face the challenge of irregular electricity supply, even with electricity access. Privatizing the energy sector in these countries also contributed to high hydroelectricity prices (Ondraczek, 2013).

Aarakit et al. (2021b) 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, innovations from the solar industry, and increased power outages were significant drives for the adoption of solar PV systems. Besides, there are tax subsidies for some solar PV systems and components, making solar PVs more affordable, thus increasing the uptake of solar PV in Uganda (Avellino et al., 2018).

However, there are challenges associated with the adoption solar PV system. According to Avellino et al. (2018), in Uganda, energy rules and regulations cut across 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 constrained Bangladesh's successful adoption of solar PVs. Most solar energy consumers depend on small scale photovoltaic plants for domestic use. However, the construction of the Soroti 10 MW solar power station in 2016, the Tororo 10 MW solar power station in 2017, the Kabulasoke 20 MW solar power station in 2019, and the Mayuge 10 MW solar power station in 2019 is expected to increase the use of solar energy on an industrial scale.

In addition to the above challenges, 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 (Mondal & Klein, 2011; Urmee & Harries, 2011; Wassie & Adaramola, 2021).

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

Solar lighting is a relevant and practical educational input since children can study for extended hours. Moreover, the electrification of health centers and schools provides safer child delivery and improved quality of education (Wassie & Adaramola, 2021). Buragohain (2012) also noted that the crime rate was reduced after solar street lighting in Indian rural villages.

On conditional that grid electricity has failed to close the energy poverty gap and solar energy's socioeconomic and environmental benefits, it is worth exploring the determinants of solar PV adoption in Uganda. There is extensive research on the role of solar PV systems in fulfilling basic electricity needs and improving the health, education, and welfare of rural households and the reasons for their adoption. There is also an inadequate examination of the determinants of solar PV adoption in Uganda. This study aims to fill this research gap.

Aarakit et al. (2021a) studied the adoption of solar photovoltaic systems in households in Uganda, but their study used different dataset. Specifically, they use the 2018 National Electrification Survey data set, while this paper employs the 2018/2019 Living Standards Measure Survey (LSMS) household data Aarakit et al. (2021a) employed a different research methodology (Conditional Mixed Process (CMP) model), while this study uses the Binary Probit and Multivariate Probit Models. The Multivariate Probit model is the most appropriate for analyzing solar PVs adoption since solar PV adoption is correlated with the use of grid electricity, kerosene, and other lighting alternatives. The study by Aarakit et al. (2021a) does not consider other lighting energy fuels in their model. Yet, solar adoption is highly correlated with these energy fuels and hence needs to be jointly estimated in a multivariate model. This study focuses on many possible determinants (wealth, savings, education, location, household size, grid-electricity prices, reliability grid-electricity supply, gender, age, and grid connection) of solar adoption in Uganda. Aarakit et al. (2021a) emphasize flexible payment mechanisms (affordability) and influential persons (social factors) as the only determinants of solar adoption in Uganda.

3. Research Methodology

3.1. Model Specification and Econometric Methodology

The econometric analysis was carried out using binary probit regression to analyze the major factors influencing the adoption and purchase of solar PVs in Uganda. Binary probit regression models examine the relationship between a binary dependent variable y and one or more explanatory variables $\boldsymbol{X}$. 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 or continuous).

The binary regression is mathematically specified as follows:

$$y_i^* = \boldsymbol{X}\boldsymbol{\beta} + \epsilon \tag{1}$$

$$y_i = \begin{cases} 1 & \text{if } y_i^* > 0 \\ 0 & \text{if } y_i^* \le 0 \end{cases} \tag{2}$$

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. $\boldsymbol{X}$ is a vector of independent variables.

While using the binary probit model, we use the whole sample but also divide the sample into urban and rural households since they tend to exhibit different characteristics in terms of fuel choice. This is done to test the consistency of our results.

For robustness checks, the study employs a multivariate probit (MVP) 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 solar PV adoption is correlated with grid electricity, the use of kerosene, and other lighting alternatives. Therefore, we estimate Multivariate Probit model analysis with four binary outcome choice variables: solar PVs, grid electricity, kerosene, and others (none of the mentioned three). The multivariate probit model has also been applied by Behera et al. (2015), Ali et al. (2019), and Wassie & Adaramola (2021) to analyze the determinants of household choices of energy fuels for lighting. Following Mullahy (2016), the multivariate probit model in this paper was formulated as follows:

$$y_{ij}^{*} = \boldsymbol{X}_i \boldsymbol{\beta}_j + \boldsymbol{u}_{ij} \tag{3}$$

$$y_{ij} = \begin{cases} 1 & \text{if } y_{ij}^{*} > 0 \\ 0 & \text{if } y_{ij}^{*} \le 0 \end{cases} \tag{4}$$

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

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

where $\boldsymbol{X}$ is a matrix of the explanatory variables; $\beta_1, \beta_2, \beta_3$ and β_4 are parameter estimates and u_{ij} are assumed to be independent and identically distributed across i but correlated across j for any i. The model is estimated using maximum likelihood estimation.

3.2. Data

We use the Living Standards Measurement Survey (LSMS) household data for 2018/2019 for Uganda. The Uganda Bureau of Statistics UBOS collected the data on behalf of the World Bank. The data consist of 3242 randomly selected households throughout the country. After data cleaning, we used 2818 observations in the analysis. The households eliminated from the sample were due to a lack of data. The data collected from the household survey included demographic and socioeconomic characteristics and energy sources. It has information on households' lighting choices: grid-electrified, solar-electrified, kerosene lighting, and other lighting fuels.

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

1) Annual household income: This is measured as total household income over one year. A positive coefficient is expected since income increases purchas-

ing power, thus leading to higher demand for solar PV systems. Guta (2018) argues that solar energy production is a luxury good, especially in low-income countries. Therefore, its adoption is likely to increase with income. Moreover, Smith & Urpelainen (2014) found a positive effect of income on solar adoption in East African countries.

2) Savings: This dummy variable takes 1 for having money saved in the bank and 0 for no savings. 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 educational level of the household head (main breadwinner in the family). It is measured as the number of years of completed schooling. A positive coefficient is expected because, with higher education, there is greater awareness of the uses and benefits of solar PV systems. Guta (2018) argues that education improves employment opportunities. This increases household income, thus the affordability of solar PVS.

4) Gender of the household head: It is a dummy variable that takes on 1 for females and 0 otherwise. Here a positive coefficient is expected. This is because, in most developing countries, females are responsible for the laborious energy acquisition (Guta, 2018). Since women are more affected by the lack of energy, they are more willing to pay for renewable energy technologies such as solar PV than their male counterparts. On the other hand, male-headed households could be wealthier, 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 pay for solar PVS, thus indicating a negative coefficient of age (Guta, 2018). However, Guta (2018) also argues that the older people may be wealthier and more likely to invest in solar technologies. Thus, a positive coefficient is expected.

6) Urban: 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 Lewis & Pattanayak (2012), urban areas are positively associated with the adoption of cleaner fuels than rural locations. Therefore, we expect solar PV system adoption to be higher in urban areas than rural ones. Besides, urban households are likely to be close to the market for solar PVs.

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 since the fixed cost can be spread 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, and hence a positive coefficient is expected. Since grid electricity and solar energy are potential substitutes, an increase in grid electricity prices may indicate higher probability of adopting solar

PVs. 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. When the grid electricity supply is regular (more extended 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 adopting solar PVs (Ondraczek, 2013; Aarakit et al., 2021b).

10) Grid connection: This dummy variable takes on 1 if the household is connected to the grid 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 PVs 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 reports the summary statistics of all variables used in this study. Only 37% of households used solar PVs, while 37% of the respondents had access to grid electricity. Most Ugandans live in rural areas, so 25% of the surveyed

Table 1. Summary statistics using 2818 observations.

Variable	Mean	Std. Dev.	Min	Max
Solar use	0.37	0.48	0	1
Grid (1 = grid access)	0.37	0.48	0	1
Urban (1 = urban)	0.25	0.43	0	1
Electricity price	689.47	78.81	572.4	771.1
Age hhhead	47.79	15.70	18	98
Household size	5.77	3	1	22
Gender (1 = female)	0.33	0.47	0	1
Electricity hrs	2.83	7.39	0	24
Saving	0.85	0.36	0	1
Income	1.1e+07	3.53e+08	−4.3e+08	1.87e+10
Education level	5.957	4.46	0	16

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

households is in urban areas. The average price of electricity per unit was 689 Ugandan shillings. The average age of the household was 48 years. The average household size was 6 members.

Regarding gender, only 33% were female-headed households. The average electricity hours available were 3 hours per day. This implies electricity is unreliable and is characterized by blackouts in Uganda. On average, 85% of the respondents saved money. The respondents had, on average, approximately 6 years of completed schooling. The average annual income of the surveyed households was UGX 11,000,000, about USD 2953 at an exchange rate of UGX 3725 per 1 USD.

We analyze the correlation matrix between variables, as presented in Table 2. The correlation coefficients measure whether and how strongly solar PV adoption relates to the explanatory variables. As expected, the correlation coefficient (−0.17) between solar use and access to grid electricity is negative, suggesting that the two energy sources are substitutes. Also, urban location, electricity prices, being a female-headed household, and electricity hours are negatively associated with the adoption of solar PVs. Income, age, household size, savings, and education are positively correlated with the adoption of solar PVs.

4.2. Determinants of Solar PVs Adoption in Uganda

Next, we examine the determinants of solar PVs adoption by applying two econometric analysis models, binary probit, and multivariate probit. Table 3 reports the results on the determinants of solar adoption in Uganda from the binary

Table 2. Correlation matrix (2818 observations).

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) Income	0.028	−0.010	0.037	1.000							
(5) electricity_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) household size	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) electricity_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) education_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, electricity_price is average electricity prices per kWh, age_hhhead is the age of the household head, household size is the size of the household, electricity_hrs is average electricity hours per day, and education_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 female and 0 for male and saving is a dummy variable taking on 1 for if household saved and 0 if household.

probit model. The study uses the estimated marginal effects in the analysis for a better interpretation.

As evidenced in model 1 in Table 3, urban negatively affects solar adoption in

Table 3. Determinants of solar PVs adoption in Uganda—probit regressions—full sample.

Variable	(1) dy/dx	(2) dy/dx	(3) dy/dx
Grid	−0.10	−0.18***	
	(0.06)	(0.06)	
Urban	−0.29***		−0.33***
	(0.07)		(0.07)
electricity_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)
Household size	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)
electricity_hrs	−0.07***	−0.08***	−0.08***
	(0.01)	(0.01)	(0.01)
Savings	0.37***	0.36***	0.37***
	(0.07)	(0.07)	(0.07)
education_level	0.04***	0.04***	0.04***
	(0.01)	(0.01)	(0.01)
Income	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	2818	2818	2818

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

Uganda. Being in an urban area reduces the probability of adopting solar PVs by 29%, and the variable is statistically significant at a 1% significance level. The marginal effect becomes larger in Model 3 after dropping access to the grid variable. Omitting access to the grid is done to avoid multicollinearity because grid access and urban areas are highly correlated. The negative marginal effect of the variable urban implies that 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 claim that urban areas are positively associated with the adoption of cleaner fuels than those in rural locations unless the reason for not adopting them is that they are already connected to the grid.

Even if Giri & Goswami (2017), Aarakit et al. (2021a), and 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 that includes both access to grid electricity and the location of the household may (since the variables are highly correlated) suffer from multicollinearity problems. Multicollinearity leads to large standard errors, thus making the access to the grid electricity variable insignificant in the model. If we omit the variable "urban", access to the grid electricity variable becomes statistically significant at a 1% significance level, as seen in Model 2. 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 female-headed household reduces the probability of adopting solar PVs by 18%, and the variable is statistically significant at a 1% significance level. This implies a higher likelihood of a male-headed household adopting solar PVs than female-headed ones. Guta (2018) found that male-headed households are less likely to adopt solar PVs than their female-headed counterparts. This finding is against 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 and hence may be more willing to pay for cleaner and more convenient energy technologies like solar PVs. Males in Uganda tend to be wealthier than women and may afford the cost of solar PVs. Wassie & Adaramola (2021) found the gender of household heads to be insignificant in their study in rural Ethiopia.

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

We find that an increase in income increases the probability of solar PV adoption. The variable is positive and statistically significant at a 1% significance level. Similar results are reported by Urpelainen (2014), Guta (2018) and 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 income on solar adoption is negligible. We argue that households with higher incomes are mainly located in urban areas and already have access to grid electricity. Hence, they may perceive solar adoption as an additional cost, and there may be a lock-in effect, thereby having a minimal income effect on solar adoption. Also, Giri & Goswami (2017) found that with an increase in income, households are less likely to use solar energy relative to electricity because electricity is a better quality energy source.

In terms of savings, households that save have a 37% probability of adopting solar PVs than those that do not. This may be because, with savings, households can afford to cover the up-front investment of solar PVs.

Concerning household size, the study finds that a unit increase in household size increases the probability of solar adoption by 5%. The variable is positive and statistically significant at a 1% significance level. Likewise, Giri & Goswami (2017) and Guta (2018) found that household size positively affects the adoption of solar PVs. This may be because the fixed cost of solar PVs can be spread among 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 of the household head, this variable's marginal effect is positive and statistically significant at a 1% significance level. An increase in the household head's education by one year increases the probability of uptaking solar energy by 4%. Similar results are reported by Giri & Goswami (2017) and Guta (2018), who argue that education increases purchasing power and awareness, hence the preference for cleaner and more convenient energy sources like solar.

Like Guta (2018), this study found that the age of the household head is 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 a minimal effect on solar adoption, as indicated by the small marginal effects in all models. Wassie & Adaramola (2021) found that the age of the household head does not influence solar PVs adoption.

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

We carried out robustness checks to examine the sensitivity of the results described in **Table 3**, and these findings are reported in **Table 4** below. The

Table 4. Determinants of solar PVs adoption in Uganda—probit regressions, using urban and rural Subsamples.

Variable	(1) Urban sub–sample marginal effects	(2) Rural sub–sample marginal effects
Grid	−0.11	−0.12*
	(0.15)	(0.07)
electricity_price	5.0e−5	4.0e−5
	(1.9e−4)	(1e−4)
age_hhd	0.001	1.5e−3**
	(0.001)	(6.7e−4)
Household size	0.06***	0.04***
	(0.02)	(0.01)
Gender	−0.13	−0.18***
	(0.14)	(0.06)
electricity_hrs	−0.08***	−0.07***
	(0.01)	(0.01)
Savings	0.58***	0.33***
	(0.21)	(0.08)
eduction_level	0.03**	0.04***
	(0.01)	(0.01)
Income	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: Figures in parentheses are Robust standard errors, ****, **, * stand for statistical significance at 1 per cent, 5 per cent, and 10 per cent levels, respectively. Grid is a dummy variable taking on 1 for access to grid-electricity and 0 for no access, electricity_price is average electricity prices per KWH, age_hhhead is the age of the household head, household size is the size of the household, electricity_hrs is average electricity hours per day, and education_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 female and 0 for male and savings is a dummy variable taking on 1 for if household saved and 0 if household.

robustness check involved dividing the total sample into two sub-samples: urban and rural households. This was done to check if our results were unaffected by the location of the households. Given that urban and rural households in Uganda exhibit different characteristics, solar adoption factors may differ by location.

Considering the urban households' sub-sample, the significant positive drivers of solar adoption are savings, education of the household head, and household size. The results of the urban sub-sample in Table 4 are similar to those reported in Table 3 above, except for savings, which now has a much bigger impact on solar adoption with a probability of 58%. The reliability of grid electricity measured by electricity hours has a negative and significant marginal effect (−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, as reported in Table 3. Variables Sensitive to sample modification are gender, grid access, age and income, which are now insignificant in the urban sub-sample. The weakening of the results in the urban subsample may be due to differences in the characteristics of rural and urban households.

Considering the rural subsample, the results in Table 4 are very similar to those reported in Table 3 regarding signs and significance. The magnitude of the coefficients changes slightly. Like the full sample results reported in Table 3, savings, education of the household head, household size, age, and income increase the probability of adopting solar in the rural sub-sample, as reported in Table 4. On the other hand, the results in the rural sub-sample revealed that female-headed households, households with access to the electricity grid, and households with reliable grid-electricity supply are less likely to adopt solar, whereas, electricity prices do not statistically significantly affect solar adoption. Similar results are reported in the full sample in Table 3.

4.3. Robustness Check Using a Multivariate Probit Model

Table 5 shows 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 and solar use suggests that the Multivariate probit model is the most appropriate for analyzing solar PVs adoption. The model compares factors affecting the adoption of various energy sources, which provides valuable insight. Subsequently, Table 6 reports the estimated multivariate probit coefficients.

Table 5. Correlation Matrix for the various energy sources.

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

Table 6 reports the results of the multivariate probit model. We observe that 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 and hence access to grid electricity; moreover, this kind of electricity is viewed as a better energy source. Access to grid electricity 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 negatively correlated with 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. The findings are in line with (Mwalule & Mzuza, 2022), who found that the level of education attained had an influence on the peoples' choices to use solar technology. Furthermore, household size increases the likelihood of using solar energy, and decreases the probability

Table 6. Determinants of solar PVs adoption in Uganda—multivariate probit model.

Variable	(1) Solar	(2) Grid−electricity	(3) Kerosene	(4) Others
Urban	−0.6674***	1.4588***	−0.136**	−0.2341***
	(0.0662)	(0.0699)	(0.0640)	(0.0644)
eduction_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)
Household size	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)
Savings	0.3621***	0.082	0.0187	−0.3301***
	(0.0709)	(0.1058)	(0.0717)	(0.0669)
income	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	2818	2818	2818	2818

Note: Figures in parentheses stand for Robust standard errors, and ****, **, * stand for statistical significance at 1 per cent, 5 per cent, and 10 per cent levels, respectively. age_hhd is the age of the household head, household size is the size of the household, and education_level is the years of completed schooling of the household head.

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 a household that saves is less likely to use other energy sources. This implies that by saving, 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 energy and reduces the likelihood of using other energy sources. This may indicate that older people are wealthier and 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 female-headed household reduces the probability of adopting solar energy but increases the likelihood of using grid electricity. Males can afford it, given that, on average, males are richer than females in Uganda. Focusing on income, though rightly singed (positive coefficient), its marginal effect on all energy sources is very minimal.

5. Conclusions and Recommendations

This study empirically examined the factors affecting the adoption of solar PVs in Uganda. The findings from the probit and multivariate probit models are that household savings, education, age of the household head, household size, and income drive the adoption of solar PVs in Uganda. Nevertheless, households in urban areas, households with access to grid electricity, households with reliable grid electricity supply, and female-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. Solar PV kits can be costly, whereas, with grid electricity, there may be less up-front investment, but you pay monthly. For liquidity-constrained households, the difference in cost profile over time might be decisive.

Given that many households in Uganda live below and around the poverty line, they cannot pay for solar panels since, in most cases, the entire investment is up-front. More research is needed through market innovation of various solar panels for further considerable cost reduction for the end-user. The government should establish credit schemes for solar provision to lessen the burden of up-front investment in solar, making it relatively affordable. The government should also educate people, mainly rural households, on the uses and benefits of clean solar energy. Education creates awareness of clean energy, such as solar energy, thus increasing its adoption.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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