Energy Economics 138 (2024) 107815

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

What drives solar energy adoption in developing countries? Evidence from household surveys across countries

Daniel Mahn [a,b], Rohan Best [c,*], Cong Wang [c], Olukorede Abiona [d]

[a] Department of Industrial Engineering, University of Concepcion, Edmundo Larenas 219, Concepcion, Chile
[b] Facultad de Economía y Negocios, Universidad Del Desarrollo, Santiago, Chile
[c] Macquarie Business School, Macquarie University, 2109 Sydney, Australia
[d] Macquarie University Centre for the Health Economy (MUCHE), Macquarie University Business School (MQBS) and Australian Institute of Health Innovation (AIHI), Level 5, 75 Talavera Road, Macquarie University, Macquarie Park, New South Wales 2109, Australia

ARTICLE INFO

JEL codes:
D10
O13
Q40

Keywords:
Bank account
Battery
Developing country
Distance to capital
Solar potential

ABSTRACT

This study investigates household solar energy uptake in developing countries by combining household surveys for 11 countries with area-level data. We use data from World Bank surveys for countries in Africa, Asia, and Central America. Our probit regressions use up to 36,653 household observations and cover actual uptake rather than intentions. The main result shows that households further from capital cities are less likely to have solar home systems. Furthermore, there are strong links between assets and solar uptake across solar types such as solar home systems, solar lighting systems, and solar lanterns. This is an important finding given the small number of prior studies that use actual uptake data for developing countries and the mixed results from prior literature. We do not find evidence that households in sunnier areas are more likely to have solar home systems across countries. This study motivates policymakers to consider greater support for households far from capital cities, in sunnier regions, and with low levels of assets.

1. Introduction

Household solar panel uptake can contribute to the pursuit of goal 7 of the United Nations Sustainable Development Goals (UN SDGs) of access to modern energy for all (United Nations: Department of Economic and Social Affairs, 2022). The adoption of household solar panels would allow for a leapfrogging from traditional to modern energy sources (van Benthem, 2015). This concept is particularly important within the framework of developing countries, partly skipping the step of grid investment, which is quite costly and delays the transition to clean energy adoption. There is also strong motivation for understanding solar panel adoption in relation to climate change mitigation, which is consistent with goal 13 of the UN SDGs on climate action (United Nations: Department of Economic and Social Affairs, 2022). This is on the background of solar panels being an alternative to electricity generated through fossil fuel combustion. In addition to policymakers' interest in solar panels in pursuit of reducing world emissions, there is also considerable interest at the individual and household levels in supporting a healthy environment. In contrast, the current level of solar panel uptake worldwide is not sufficient to achieve important targets.

Research evaluating the factors driving solar uptake is sparse for developing countries. For example, <30% of quantitative solar uptake studies are for countries outside of the Organization for Economic Cooperation and Development (OECD) (Best et al., 2023), despite these countries accounting for most of the global population. Household-level studies for developing countries also tend to have relatively small samples, averaging approximately 1500 (Best et al., 2023).

This paper seeks to provide further understanding of the factors determining the adoption of solar panels across developing countries by combining World Bank surveys from 11 developing countries. We focus on solar energy generation by photovoltaic panels to produce electricity at the household level. We assess solar panel uptake from surveys for Cambodia, Ethiopia, Honduras, Kenya, Liberia, Myanmar, Nepal, Niger, Nigeria, Rwanda, and Zambia. This combination of household surveys is possible due to the commonality of variables across countries. Our analysis covers 43,467 households and has a maximum regression sample size of 36,653 households due to consistency in the data structure. In addition, we link regional and national variables for economic

---

* Corresponding author.

E-mail addresses: dmahn@udec.cl, dmahnb@udd.cl (D. Mahn), rohan.best@mq.edu.au (R. Best), cong.wang@mq.edu.au (C. Wang), olukorede.abiona@mq.edu.au (O. Abiona).

https://doi.org/10.1016/j.eneco.2024.107815
Received 19 September 2023; Received in revised form 25 July 2024; Accepted 30 July 2024

and energy characteristics to household data. This research fills the gap on the importance of background characteristics in the adoption of clean energy in low-income countries. The inclusion of demographic, socioeconomic and geographical factors helps to cover extensive factors that may be relevant for targeting policy in this regard.

The large and integrated dataset allows us to provide key insights into the main determinants of solar panel adoption across these countries and regions. In the analysis, we find a novel result that indicates that the distance of a province to the country's capital city is negatively related to household solar panel adoption. We also find that having assets and financial accounts is important for solar panel adoption. In addition, dwelling ownership is a substantial facilitator of solar panel uptake. This result is complemented by the establishment of a positive relationship between the number of people in the household and solar panel adoption. Furthermore, rural location appears to incentivize solar panel adoption. This is the case even when controlling for access to the national electricity grid. Finally, this paper bridges the gap that enables the linkage of evidence to policy. In the analysis of our results, we examine the actual adoption of solar panels, thereby enhancing policy formulation and facilitating solar uptake, which matters in our context—rather than hypothetical data commonly used in the literature.

In summary, the three main areas of contribution of this paper include (i) comparative analysis across countries with greater breadth than prior studies, where cross-country differences highlight Cambodia as a country for which future research would be highly beneficial; (ii) the assessment of the robustness of policy-relevant relationships between socioeconomic variables and solar-technology uptake, which is crucial given the mixed prior findings, as outlined in Section 1.3; and (iii) exploratory area-level analysis of the link between geographical variables such as distance to the country's capital and practical photovoltaic potential of a region (PVOUT) on solar uptake, which is important for motivating future policy attempts to better capitalize on sunny, higher irradiance conditions.

The remainder of the study is organized as follows. The rest of Section 1 presents some context for low-income countries and solar use, Section 2 presents the research questions, Section 3 describes the data and econometric approach, Section 4 examines the results, Section 5 discusses possible explanations for the results, and Section 6 presents the policy implications and conclusions.

1.1. Solar energy adoption: context for low-income countries

Solar energy systems are often considered substitutes for defective electricity grids in developing countries. While this perspective is valid due to inefficient grid transmission, solar energy sometimes serves complementary energy purposes as well, similar to the approach in developed countries (Lay et al., 2013). For the former, solar systems can act as a backup to the electricity grid. Additionally, in cases where electricity grid connections are too expensive, solar systems may be viable alternatives.

Another important reason for the essence of this research is the body of evidence that establishes a negative association between poverty level and access to electricity from the national grid (Poblete-Cazenave and Pachauri, 2021). The fact that a large proportion of people from the countries included in our sample are living below poverty levels suggests that they may also be energy poor as well, with restricted access to electricity due to low-income levels. In this case, solar energy adoption seems to be an immediate option useful for bridging the critical energy gap, if affordable (Asghar et al., 2022). Hence, there is a need to understand the link between socioeconomic characteristics and solar energy adoption in the current context.

The inclusion of countries from different continents enables us to investigate potentially differential patterns of the determinant factors, especially as the depth of poverty may differ across geographical zones. Table A1 presents the historical cross-country national electricity access over a period of two decades (2000−2021). The summary statistics show an interesting pattern with extensive time and spatial variation in access to electricity for our sample of countries. It is not surprising that electricity access for Honduras (the only central American country) is the only comparable context to world patterns, while access has significantly increased but remains much lower in sub-Saharan Africa.

The size of solar panel systems is important in the context of developing countries. The multitier framework (MTF) provides a useful approach for categorizing solar systems (Dubey et al., 2019). The categories include (i) very small energy sources such as solar lanterns where a single light is powered by solar energy and (ii) medium solar systems for solar lighting systems. These systems can be sufficient for powering a small number of appliances in a household, including lights; and (iii) larger systems, also called solar home systems. However, the sizes of (iii) may not necessarily compare to the sizes of similar solar panels in developed countries due to capital constraints.

Solar panel uptake has great potential for providing access to clean energy in countries with high levels of solar radiation, but the diffusion of solar technology has remained low in low-income countries (Shahsavari and Akbari, 2018). Potential reasons include the high cost of capital for residents in these countries and a lack of investment capacity for diffusion (International Energy Agency, 2022). At the micro level, the lack of assets and access to credit facilities also creates important barriers to the adoption of solar panels in developing countries (Aarakit et al., 2022; Best, 2023a).

1.2. Methods and approaches for prior studies

Most studies of solar uptake for countries outside of the Organization for Economic Cooperation and Development (OECD) have used cross-sectional analysis. Only one of 44 household-level studies have used a longitudinal design (Best et al., 2023). That study used a sample of 1530 households to assess two time periods (Aklin et al., 2018a). Another methodological aspect is that most studies of non-OECD countries have investigated intentions for hypothetical solar uptake; 30 of 44 studies have analysed solar uptake intentions (Best et al., 2023). This contrasts with studies of OECD countries, which are more likely to use actual solar panel uptake (Best et al., 2023). There are several possible explanations for this outcome. Lower solar panel uptake in non-OECD countries is one contributing factor. In addition, data on actual uptake may be more comprehensive in OECD countries. Regardless of the reason, the relative undersupply of developing country studies using the actual uptake of solar panels is one motivation for our study of actual solar panel adoption across 11 developing countries.

1.3. Mixed results in prior studies

There are mixed findings from prior studies across a range of variables (Alipour et al., 2020; Best et al., 2023). This may be related to different study contexts, including different variable definitions. These mixed results motivate further research that seeks to broaden understanding across various contexts. The first step is to understand the extent of diversity in prior results, as discussed in this section. In Section 4 below, our study aims to contribute by combining and analysing World Bank surveys for 11 developing countries, where possible, based on variable similarity. We summarize some diverse findings in Table 1.

In general, the results for the impact of income on solar panel adoption tend to be very mixed (Best and Chareunsy, 2022). This includes a mix of results across four possibilities: negative, positive, insignificant, or not included. However, apparently negative impacts of income are uncommon in the developing country context. A few exceptions include studies of Iran, India, and Bangladesh (Bashiri and Alizadeh, 2018; Irfan et al., 2021; Zaman and Borsky, 2021). Nonsignificant coefficients for income are also quite uncommon for developing country studies, although studies of China and Kenya are two examples (Best, 2023a; Wang et al., 2021). Positive coefficients for income are more common for developing countries.

Table 1
Diverse findings in some prior studies on developing countries.

Authors	Year	Country	Income	Age	Education
Bashiri and Alizadeh	2018	Iran	−	0	+
Best	2023	Kenya	0	0	+
de Freitas	2022	Brazil	+	−	+
Guta	2018	Ethiopia	+	+	+
Irfan et al.	2021	India	−	−	na
Jayaweera et al	2018	Sri Lanka	na	+	+
Kurata et al.	2018	Bangladesh	+	+	0
Shahid et al	2022	Pakistan	na	na	0
Smith and Urpelainen	2014	Tanzania	+	na	0
Wang et al	2021	China	0	0	0
Zaman and Borsky	2021	Bangladesh	−	na	na

Findings on the positive (+), negative (−) and insignificant (0) effects of income, age and education on solar energy use. "na" means not applicable (i.e., not included).

Most studies of non-OECD countries do not control for the age of a household respondent. However, age could impact solar adoption intentions or actual uptake since there may be patterns in the way people make plans at different ages. When age is included, it is usually a linear term (i.e., without allowing for a nonlinear distribution). Five exceptions to studies allowing for age distributions to be nonlinear include those for Bangladesh, Brazil, China, Ethiopia, and Sri Lanka (de Freitas, 2022; Guta, 2018; Jayaweera et al., 2018; Kurata et al., 2018; Liu et al., 2023). There is a mix of findings across negative, positive, and insignificant coefficients for studies including age.

Education is often found to have a positive influence but has also been found to have a negative (Aklin et al., 2018a) or insignificant impact. Some examples of insignificant education impacts for household studies of developing countries include those for China (Wang et al., 2021), Tanzania (Smith and Urpelainen, 2014), Bangladesh (Kurata et al., 2018), and Pakistan (Shahid et al., 2022).

2. Research questions and theoretical framework

We undertake an explorative study, given the very small number of previous studies using household surveys to assess actual solar panel uptake in developing countries. Our study is also uncommon in its combination of household surveys for 11 different countries across three continents. The research questions addressed in this paper are as follows:

- What are the socioeconomic or demographic variables that drive different types of solar use? (Section 4.1)
- Is proximity to the national capital a factor that affects solar panel adoption? (Section 4.2)
- Does solar radiation availability drive solar panel use? (Section 4.2)

To explore these research questions, theoretical frameworks can be useful to guide our analysis. Prior research has used many different frameworks, including diffusion of innovations literature (Rogers, 2003), the Bass diffusion model (Bass, 1969), the theory of planned behaviour (Ajzen, 1991), and value-belief-norm theory. The theory of planned behaviour is of interest because it provides a broad social framework for understanding decisions and related incentives. This can motivate a pragmatic perspective where many variables related to social aspects or incentives are included in the analysis. For example, government incentives to support the uptake of solar panels are a driving factor in many countries, such as Australia (Best et al., 2019). However, developing countries may not have the resources to support solar panel uptake. In some cases, support may also be directed to suppliers rather than households (Best, 2023a). In cases where policy support exists, this support often varies by location, so location binary variables can partly control for policy differences.

General economic perspectives are also useful for complementing social theories. For example, income or wealth effects and property rights are fundamental economic concepts that may be expected to be important for solar panel adoption. For instance, households with more wealth or income might be less constrained in the installation of solar panels. Households who own their home would also avoid a potentially major constraint where renting households do not have permission or incentives for solar panel adoption.

The consideration of geography and aspects related to distance are also useful for our context. It is possible that technological knowledge spillovers are localized to some extent (Keller, 2002). More generally, there may be other barriers to the diffusion of solar energy systems across regions. This is similar to the disadvantage faced by rural households in terms of available economic opportunities. Other types of regional disadvantage, such as university admissions, have been suggested in other contexts (Lin et al., 2023).

Furthermore, the role of urban and capital regions in developing countries is also a major reason why we focus on the capital regions of these 11 countries. It is widely understood in the current literature that capital cities often play a major role in driving growth and development through the adoption of new technologies ahead of rural areas (see, e.g., Jedwab et al., 2021; Dingel et al., 2021, Chauvin et al., 2017; Sørensen, 2016). However, there may be exceptions to this pattern depending on the type of technology. For solar home systems, which are often substitutes for electricity grid access, there is evidence suggesting that rural areas are more likely to have solar technologies (Aarakit et al., 2022; Irfan et al., 2021; Rahut et al., 2018). Rural areas can also face barriers to accessing other energy inputs, such as kerosene (Rehman et al., 2005), making solar systems a possible substitute that does not require frequent access to markets.

3. Method and data

3.1. Data

We draw our datasets from two main sources: the Multi-Tier Framework (MTF) Survey for household data, and for solar potential at province- and country-level aggregates, we draw data from the Global Solar Atlas.

Household solar use data were obtained from the Multi-Tier Framework (MTF) Survey, which is a tool developed by the World Bank's Energy Sector Management Assistance Program (ESMAP, 2020) to assess the status of energy access in low- and middle-income countries. It is based on the MTF approach, which recognizes that energy access is a multidimensional concept that goes beyond simply providing households with access to electricity and considers other factors such as reliability, affordability, and adequacy. The MTF Survey collects data on various aspects of energy access, including the type of energy source used, the quality and reliability of energy services, and the affordability of energy for households. The survey also collected data on socioeconomic factors that may affect energy access, such as income and education levels. The quality of the data has allowed for informing policy decisions and identifying areas where interventions are needed to improve energy access.

Solar data are available from the Global Solar Atlas,[1] an online platform funded by the Energy Sector Management Assistance Program (ESMAP) from the World Bank. This dataset includes high-resolution maps of solar resource potential, including solar irradiation, temperature, and other relevant factors, for >200 countries and territories. These maps can be used to assess the potential for solar energy generation at specific locations, such as rooftops, solar farms, and other installations. The platform also provides information on local solar energy policies and regulations, as well as data on the cost of solar energy technologies and their deployment potential in different regions. This

---

[1] Available at https://globalsolaratlas.info/

information can be useful for policymakers, energy planners, investors, and other stakeholders who are interested in expanding the use of solar energy. Finally, it has also been used previously in different studies for estimating solar input availability (Abdeladim et al., 2020; Brent et al., 2020).

To construct our multicountry dataset, we were able to overcome several limitations of the available data. First, while solar data are available globally at the provincial and country levels, the MTF survey is available only in selected countries; thus, the coverage of our study is constrained by the latter. Second, while the MTF framework was designed as a questionnaire with the same set of questions and questionnaire design, in the application of this framework in each country, several of them changed their question wording and codification into values. For example, questions where sex was defined as binary in one survey were defined in others with values such as "1" or"2″ or with different question numbers defined differently. To overcome this issue, the dataset had to be merged on an ad hoc basis by harmonizing each survey's question codes into one and then recodifying all questions manually. After the datasets were merged, the frequencies of each variable were compared between countries to identify any discrepancies or possible errors. Arbitrarily, we selected the Kenya questionnaire as the default, following a previous study from a recent paper (Best, 2023a), and then set the rest of the sample to follow its variables and codebook.

Third, questions regarding monetary amounts, such as income or property values, were all transformed to US dollars using the first day of the month of the survey publication as the reference date. While the unit of study is the household, we consider the household head of the family as the reference for demographic characteristics. In the cases where more than one head was defined (44 cases of the complete sample, in total), we arbitrarily used as a rule selecting the "older working integrant of the family". The full details of the variables and the cleaning process are available in the complementary appendices and replication codes.

Fourth, the answer coverage also differed between each country's sample respondents. In some countries, such as Kenya, respondents answered income-related questions such as main occupational income or land value; however, these answers in other countries are sometimes scarce. Thus, some valuable information that we could use from the sample had to be discarded or used in a smaller dataset. Moreover, regarding household location, in most cases, the chosen administrative region was the European NUT-2 equivalent. While there are different political and administrative obligations across countries, we used province dummies to summarize differences across provinces and countries. This explains a large portion of the variation, as is evident in Section 4. A strength of our study is the cross-country comparison, but a caveat exists in that some country differences are not separately identified from the province binary variables, which effectively cover many regional differences.

Finally, following Best (2023a) and for comparison purposes, we exclude a sample of 195 households who had chosen not to obtain a grid connection because of satisfaction with their current energy situation. This could theoretically relate to having solar devices, so exclusion helps to avoid concerns about reverse causality.

Table 2 provides details of country composition (sample availability determined by factors highlighted above), and Fig. 1 details its worldwide dispersion. Most of the countries are located in sub-Saharan Africa, while three others are in Asia, and one country, Honduras, is in Central America.

3.2. Dependent variables

We use four different dependent variables that are based on having specific types of solar energy systems. These different solar types include solar home systems (SHSs), solar lighting systems (SLSs), solar lanterns, and solar batteries. First, SHSs are any solar device in the largest capacity category and are thus larger in capacity than solar lighting systems and solar lanterns (Dubey et al., 2019). An SHS can generally power appliances such as televisions. Second, SLSs have small/medium capacity and are sufficient for Tier 1 electricity access classification on a scale ranging up to Tier 5 for an entire household (Dubey et al., 2019). Third, a dependent variable refers to a household having at least one solar lantern. Solar lanterns power only one light bulb. Finally, we also assess outcomes where "solar" is the electricity source used to recharge a battery. While we focus our analysis on drivers of SHSs, as they have the capacity to replace the full use of grid electricity, we use the remaining less powerful devices for additional analysis. The motivation for this is to determine whether the drivers for use differ between them.

Table 2
Country data availability.

Country	Survey Publication date	Sample size	Number of Provinces	Code
Cambodia	Jun-18	3771	25	KHM (4)
Ethiopia	Jun-18	4317	11	ETH (1)
Honduras	Nov-19	2815	16	HND (2)
Kenya	Nov-19	4590	8	KEN (3)
Liberia	Dec-20	3903	16	LBR (5)
Myanmar	May-19	3446	15	MMR (6)
Nepal	Jul-19	6000	7	NPL (9)
Niger	Jun-20	4049	8	NER (7)
Nigeria	Jun-20	3669	7	NGA (8)
Rwanda	Jun-18	3295	5	RWA (10)
Zambia	Jun-19	3612	10	ZMB (11)
Grand Total		**43,467**	**128**	

Details of surveyed countries from the MFT.

3.3. Area-level explanatory variables

For solar data availability, we draw two different measures from the Global Solar Atlas[2]: the photovoltaic practical potential of a region (PVOUT) and the levelized cost of energy (LCOE).

First, the practical solar PV potential (level 1) is the power output achievable by a typical photovoltaic system (PVOUT). The measure considers an adjusted theoretical potential, which is the sum of direct and diffuse irradiation components received by a horizontal surface and measured in kilowatt hours per square meter (kWh/m2). Then, it simulates the conversion of available solar resources to electric power considering the impact of air temperature, terrain horizon, and albedo, as well as module tilt, configuration, shading, soiling, and other factors affecting system performance. PVOUT is the amount of power generated per unit of installed PV capacity over the long term (the specific yield), measured in kilowatt-hours per installed kilowatt peak (kWh/kWp).

Second, we assess the economic photovoltaic potential as expressed via a simplified levelized cost of energy (LCOE), which describes how much it would cost to produce a unit of energy. Apart from the PVOUT value, the cost of photovoltaic technology, overall capital expenditure, operation costs, and discount rate are considered over a typical PV plant lifetime. The metric enables the comparison of solar energy to other energy generation technologies. The LCOE, which was conceived as a snapshot in 2018, ranged globally from less than USD 0.06 to over USD 0.26 per kWh, with a significant part of the globe scoring below USD 0.12.

In addition, for each country, we consider two other measures: one for location and one for per capita energy use. The national power consumption, from the Global Photovoltaic Power Potential Study (in kWh per capita), measures the production of power plants and combined

---

[2] Available here: https://globalsolaratlas.info/global-pv-potential-study

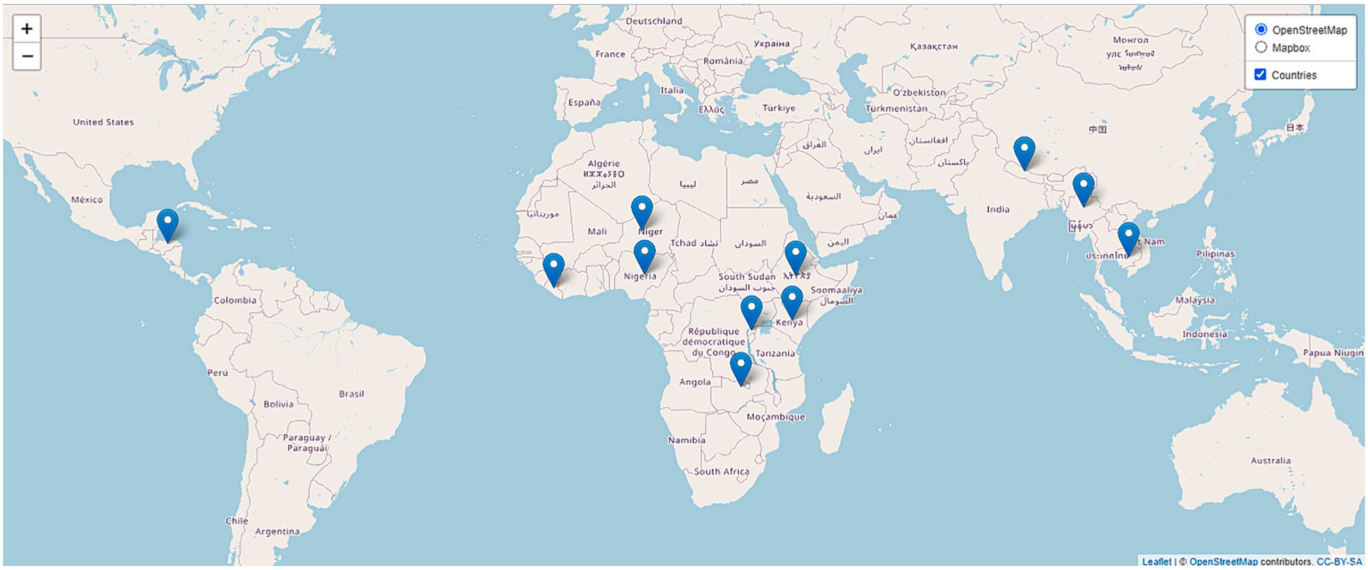

Fig. 1. World map with each country's data availability.
World map with a dot in every available country for sampling.

heat after stripping out transmission, distribution, and transformation losses and the own use of power plants. This measure translates roughly to the per capita energy use in each area. We also include the province distance to the capital city for possible regional favouritism. This accounts for the possibility of politicians' behaviour, potentially influencing the household decision to adopt. For example, more incentives may be given to certain favoured provinces, which may be closer to capital cities. Moreover, capital cities could receive the largest number of resources, including resources for renewable energy adoption, from political leaders. Therefore, provinces closer to the capital city could experience positive spillover effects from this regional preferential treatment (see, e.g., Lin et al., 2023). This is a pointer to the interaction of political factors and energy adoption patterns (Kwan, 2012; Bayer and Urpelainen, 2016).

3.4. *Household-level explanatory variables*

We included demographic, economic, and house-related characteristics for each household. For demographic characteristics, we considered the gender of the household head, age, marital status, and whether they had ever attended school. Related to the household characteristics, we control for the following factors: whether the household is in a rural area; the number of inhabitants; whether the family owns the household; whether more than one family shares the household; the number of rooms occupied excluding the kitchen, toilet, and bathroom; the main material of the walls of the dwelling; whether the household is connected to the grid; and the main reason for not being connected to the grid (if not). For economic controls, we include whether the household has a bank account from a formal or informal institution or a mobile account, whether it is self-employed, and the main income level.

3.5. *Methodological approach*

The model used in the paper, based on variables assessed in previous literature reviews and meta-analyses (Alipour et al., 2020; Best et al., 2023), is shown in Eq. (1):

$$S_h = \alpha + \boldsymbol{H'}_h\beta + \boldsymbol{A}'_h\gamma + \varepsilon_h \qquad (1)$$

A probit model is used to account for the dichotomous nature of the dependent variables for each household (h). Linear probability models also produce similar results. The dependent variables, in separate regressions, are for households with a solar home system, solar lighting system, solar lantern, or solar battery. These variables are defined in greater detail in Table 3. Eq. (1) also shows the two main groups of explanatory variables: household-level variables (H) and area-level variables (A).

4. Empirical findings

4.1. *Associations between household characteristics and solar use*

In Table 4, we report the socioeconomic and demographic determinants of solar adoption by households. Column 1 contains controls for socioeconomic characteristics; in column 2, we add grid coefficients; and in column 3, we add income brackets. In columns 4 to 6, we repeat the same analysis but focus only on households that are unconnected to the grid.

There are positive and significant coefficients for variables related to assets when explaining solar uptake, as shown in Table 4. These include variables for having a formal banking account (but not for having an informal account), having a mobile money banking arrangement, having land with large values, and being the owner of the dwelling.

Regarding the grid coefficients, not being connected to the grid because installation costs are too expensive has a negative link to solar uptake (with respect to being too far away as the reference category). This suggests capital constraints. Additionally, households that are connected to the grid have less solar panel use, even when controlling for the rest of the covariates in column 2, including rurality. This is intuitive since grid and solar home systems are substitutes; this substitutability has also been mentioned in prior research (Aklin et al., 2018b).

The material used for dwelling construction also has a significant negative influence on solar home system investment. Households that have traditional mud structures are less likely to have solar home systems. Finally, focusing on the unconnected sample does not substantially change the coefficients.

Separate results for each country in the supplementary files reveal that there is a negative and significant relationship between having a bank account and solar uptake for Cambodia. This is the only country with a negative and significant coefficient for the bank variable. The results in Table 4 still show a positive and significant coefficient for the bank variable, given that province-level binary variables are included.

Table 3
Variable descriptions.

Variable	Description	Source
Dependent		
Solar home systems (SHS)	Binary if has a Solar home system. SHS power two or more light bulbs and appliances such as televisions, irons, microwaves, or refrigerators.	MTF
Solar lighting systems (SLS)	Binary if has a solar lighting system. SLS power two or more light bulbs and allow part or the entire household to be classified in Tier 1 for Capacity (Very low load, between 3 and 49 W) (Dubey et al., 2019).	MTF
Solar lanterns	Binary if has a Solar lantern, which can power a single light bulb and allow only part of the household to be classified in Tier 1 for Capacity.	MTF
Solar battery	A binary variable equal to one for households where "Solar" is the electricity source used to recharge a battery.	MTF
Location Solar energy outputs		
PV Practical Potential (PVOUT)	Average practical potential (PVOUT Level 1, kWh/kWp/day), long-term. Power output achievable by a typical PV system.	GSA
PV Cost of energy (LCOE)	Average levelized cost of energy (USD/kWh), 2018. Describes how much it would cost to produce a unit of energy.	GSA
Location related controls		
Distance to capital	Geodesic distance from each province centroid to its country capital, in kilometres. Coordinates were obtained with ggmap and ggplot2 R libraries, using georeferenced data from Google, and distances calculated with the geosphere Rlibrary.	Google Earth
National power consumption	Electric power consumption (kWh per capita), 2014.	World Bank
Household Asset-related controls		
Rural	A binary variable equal to one for nonurban households.	MTF
Bank	A binary variable equal to one for households with a bank account holder in a formal institution.	MTF
Informal	A binary variable equal to one for households with an account holder in an informal institution.	MTF
Mobile money	A binary variable equal to one for households with a mobile money account.	MTF
Top Value	A binary variable equal to one for households with an agricultural land that is owned by the household in the top 33% tier of value within each country.	MTF
Dwelling owned	A binary variable equal to one for households who own their dwelling.	MTF
Rent-free	A binary variable equal to one for households who use their dwelling for free, as opposed to renting.	MTF
Dwelling type	A variable with three categories: 0. A single house occupied by one household; 1. A group of enclosed dwellings occupied by one household 2. Other dwelling types.	MTF
Mud	A binary variable equal to one when the main material of the walls of the dwelling is reported as mud bricks (traditional dwelling).	MTF
Grid access choice	A variable with four categories: Connected to the electricity grid; Not connected mainly because the grid is too far away or not available (base); Not connected mainly because of the high cost of connection; Not connected mainly because of another reason.	MTF
Extra Sociodemographic controls		
Rooms	The number of rooms occupied by the household, excluding the kitchen and bathrooms.	MTF
Income	A variable for the monthly income from the *main* occupation of the household head, in a scale of 3 for low, medium (base) and high income.	MTF
Self-employment	A binary variable equal to one where the household head's main occupation was self-employment over the last 12 months.	MTF
Female	A binary variable equal to one when the household head is female.	MTF
People (#)	The number of people who live and eat their meals in the household.	MTF
Marital status	A binary variable equal to one when the household is married (mono or polygamous). This variable has low availability.	MTF
School	A binary variable equal to one when the household head has ever attended school. This ignores quantity of schooling years due to data availability.	MTF
Age	The age of the household head in years.	MTF

Sources are the Multi-Tier Framework Survey (MTF), Global Solar Atlas (GSA), World Bank, and Google Earth. Further statistical details are available in the appendix.

4.2. *Associations between area-level characteristics and solar panel use*

In Table 5, we replace province dummies with variables for national and regional characteristics. We exclude Cambodian households from Table 5. This is because it is not possible to account for the unusual negative link between bank accounts and solar uptake in Cambodia with province or country dummies when using other national and provincial variables. While national power consumption (per capita) has a positive effect on solar panel use, there is a significant negative coefficient for the province distance to the country's capital when explaining solar panel uptake. These results hold for both the full sample and the subset of households that are unconnected to the national grid.

Given the exclusion of province dummies in Table 5, there is the possibility that other coefficients in Table 5 may be less precisely estimated compared to other tables. However, most of the results are similar to those in Table 4 in terms of the signs of the significant coefficients. One exception is the sign for the higher income coefficient, which is positive in Table 4 but negative in Table 5. This does not pose a problem given how mixed prior results are for income (Table 1) and the surprisingly complex relationship between income and solar panel uptake (Best and Chareunsy, 2022). For the income coefficients, we focus on the positive relationship from Table 4 since province dummies are included in Table 4.

In Table 6, we report probit regressions for how solar availability affects solar home system preference. In columns 1, 3, and 5, we report the results for practical photovoltaic potential (PVOUT). In columns 2, 4, and 6, we present the results for the cost of solar energy (LCOE). Columns 1 and 2 use national-level data for PVOUT and LCOE, so we are unable to include province or country dummies due to the threat of high multicollinearity. We partly address this in columns 3 and 4 by using provincial-level data for PVOUT and LCOE, along with country dummies. Columns 5 and 6 also control for income.

Our results are statistically significant at the 1% level in columns 1 and 2. For solar radiation (PVOUT), there is a negative relationship. This would indicate that sunnier regions do not have greater solar panel uptake. However, we do not interpret this as a causal effect, as it likely reflects unobserved heterogeneity. The coefficients are not statistically significant when more detailed variables and controls are included, such as in columns 3 and 5. The results in Table 6 are consistent with the narrative that there is an absence of strong evidence that sunnier regions

Table 4
Probit results for solar home systems.

	(1)	(2)	(3)	(4)	(5)	(6)
	Full sample			Unconnected only		
Variables	Solar Home system	Solar Home system	Solar Home system	Solar Home system	Solar Home system	Solar Home system
Rural dwelling	0.4509***	0.0972**	0.1968***	0.1217**	0.0941	0.1618**
	(0.0000)	(0.0165)	(0.0000)	(0.0408)	(0.1212)	(0.0168)
Account in Formal banking	0.2091***	0.4000***	0.3617***	0.4766***	0.4594***	0.4082***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Account in Informal banking	−0.0126	−0.0057	−0.0302	−0.0589	−0.0553	−0.0543
	(0.7640)	(0.8977)	(0.5510)	(0.3205)	(0.3570)	(0.3987)
Mobile banking	0.3155***	0.4019***	0.4264***	0.3770***	0.3922***	0.4223***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Top Value Land	0.1369***	0.2211***	0.1861***	0.4038***	0.3736***	0.3631***
	(0.0016)	(0.0000)	(0.0004)	(0.0000)	(0.0000)	(0.0000)
Owner of dwelling	0.4377***	0.3109***	0.2428***	0.2754**	0.3053**	0.3396**
	(0.0000)	(0.0000)	(0.0013)	(0.0241)	(0.0130)	(0.0134)
Free of rent	0.3723***	0.2356**	0.1728	0.2088	0.2376	0.2863*
	(0.0000)	(0.0157)	(0.1054)	(0.1625)	(0.1143)	(0.0894)
Dwelling: Single house occupied by one household	0.0598	−0.0171	0.0582	0.0082	0.0317	0.0208
	(0.2019)	(0.7279)	(0.2815)	(0.9067)	(0.6546)	(0.7820)
Dwelling: Group of dwellings occupied by 1 household	0.0956	0.0077	0.0571	0.0004	0.0066	−0.0144
	(0.2692)	(0.9323)	(0.5376)	(0.9972)	(0.9537)	(0.9004)
Walls Material: adobe	−0.0724*	−0.1938***	−0.2456***	−0.3155***	−0.2977***	−0.3229***
	(0.0681)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Household size	0.0314***	0.0316***	0.0372***	0.0410***	0.0386***	0.0464***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Grid: Connected		−1.1653***	−1.2606***			
		(0.0000)	(0.0000)			
Grid: Unconnected, Installation too expensive		−0.3939***	−0.4303***		−0.4380***	−0.4379***
		(0.0000)	(0.0000)		(0.0000)	(0.0000)
Grid: Unconnected, Other reason		−0.0586	−0.1178**		−0.0634	−0.1056**
		(0.1913)	(0.0151)		(0.1924)	(0.0425)
Lower income			−0.0038			0.0160
			(0.9328)			(0.7802)
Higher income			0.0778*			0.1735***
			(0.0872)			(0.0029)
Constant	−3.5093***	−2.7880***	−2.4279***	−2.8666***	−2.8281***	−2.9039***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Province dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	31,391	31,275	19,878	11,391	11,282	7636
Overall R-Square	0.320	0.384	0.375	0.375	0.387	0.357

Probit regression results for solar home system use. Columns 1 to 3 show the results for the full sample, and Columns 4 to 6 only consider households that are unconnected to the grid. p values in parentheses. Additional regressions for each country are available as supplementary material *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

have more solar panels. In other words, there is no positive and significant relationship for PVOUT; instead, we find a negative and significant coefficient in our initial exploratory results in column 1 and then nonsignificant coefficients with more detailed variables. These results have strong policy implications, as they reveal an opportunity for policymakers to do more in supporting solar panel uptake in sunnier regions.

4.3. Additional analyses

In Table 7, we report whether household socioeconomic and demographic characteristics are linked to the use of four different solar types: SHS, SLS, solar lights and solar batteries. The results in column 1 are the same as the reported results in Table 4 column 2 and are included again for comparison. The results show that drivers using different solar types are fairly similar, with some differences. One difference is that asset variables are less significant for the smaller sample for which battery data are available. This includes nonsignificant coefficients in column 4 for having an account in a formal banking institution, having land with a large value, and being the owner of the dwelling. Another difference, which is intuitive, is that the wall type is less important for smaller solar types such as solar lanterns. These devices are portable and do not rely on physical housing characteristics.

There is similarity in the results in Table 8, which have additional control variables, but for smaller household sample sizes due to restrictions from data availability. The additional control variables also produce some interesting results. There is some evidence of a positive relationship between income and solar uptake, with positive and significant coefficients for higher income when the reference is medium income. However, this effect is only statistically significant if the households are unconnected to the grid. There are positive coefficients for the education variable in each column.

4.4. Robustness checks

To test our results' robustness, we consider usual sources of bias, such as measurement error, unobserved or omitted variables and simultaneity (Green, 2018). The results of these tests are similar to those in the baseline models and are reported in the Appendix.

First, following (Best, 2023a), we explore an entropy balancing method. This matching approach is appropriate for observational data where randomized controlled trials are not undertaken (Athey and Imbens, 2017; Hainmueller, 2012; Hainmueller and Xu, 2013). The method involves assessing a binary 'treatment' variable. For example, having a bank account can be used to classify households into the 'treatment' group, while other households are classified into the "control" group. Entropy balancing aims to match the two groups by

Table 5
Determinants of the adoption of a solar home system (SHS), including area-level energy use and proximity to the capital city.

	(1)	(2)
	Full sample	Unconnected only
Variables	Solar Home system	Solar Home system
Rural dwelling	0.0339	0.0838
	(0.4650)	(0.1682)
Account in Formal banking	0.3547***	0.3914***
	(0.0000)	(0.0000)
Account in Informal banking	−0.0875	−0.1146*
	(0.1004)	(0.0794)
Mobile banking	0.0874*	−0.0027
	(0.0826)	(0.9652)
Top Value Land	0.2718***	0.3150***
	(0.0000)	(0.0000)
Owner of dwelling	0.2818***	0.2789**
	(0.0001)	(0.0331)
Free of rent	0.1881*	0.2788*
	(0.0900)	(0.0879)
Dwelling: Single house, 1 household	0.3851***	0.4971***
	(0.0000)	(0.0000)
Dwelling: Group of dwellings, 1 household	0.2194**	0.2664**
	(0.0167)	(0.0164)
Walls Material: adobe	−0.2503***	−0.3262***
	(0.0000)	(0.0000)
Household size	0.0188***	0.0129
	(0.0063)	(0.1372)
National power consumption (pc)	0.0038***	0.0050***
	(0.0000)	(0.0000)
Distance to country's capital	−0.0007***	−0.0012***
	(0.0000)	(0.0000)
Lower income	−0.1020**	−0.1276**
	(0.0225)	(0.0175)
Higher income	−0.1080**	−0.0814
	(0.0249)	(0.1576)
Grid: Connected	−1.1331***	
	(0.0000)	
Grid: Unconnected, Installation too expensive	−0.5135***	−0.5238***
	(0.0000)	(0.0000)
Grid: Unconnected, Other reason	−0.3924***	−0.3874***
	(0.0000)	(0.0000)
Constant	−2.0820***	−2.1982***
	(0.0000)	(0.0000)
Province dummies	No	No
Observations	15,827	6872
Overall R-Square	0.148	0.0969

Probit regression results for solar home system use, including grid characteristics. Column 1 shows the results for the full sample, and Column 2 considers only households that are unconnected to the grid. p values in parentheses. Additional regressions for each country are available as supplementary material*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

weighting the control group to produce covariate moments that match the treatment group as closely as possible. Second, we repeat all regressions from our analysis by dropping from the sample one country at a time. This is done to check whether any country in particular is driving much of the main effects. The results from the robustness checks are similar to the reference results in Table 4. We also produce similar results with linear probability models to show that the results are not sensitive to a modelling choice.

5. Discussion

In our analysis, we discover results with interesting insights into solar use. Our findings not only provide evidence from the perspective of developing economies where there is a scarcity of literature but also strengthen the general body of evidence—developed countries inclusive. First, we found similar results between our study of 11 developing countries and the study of Kenya by Best (2023a). The positive association between household assets and solar panel uptake in this paper is reflected in our results from the perspective of the value of land and formal bank accounts. This is important due to the large extent of diversity in prior solar uptake studies and the relative undersupply of research on developing countries (Alipour et al., 2020; Best et al., 2023). Second, we also find some similarities between our results and those of developed countries. In particular, assets are key drivers of solar uptake in the minority of developed-country studies which include asset variables, rather than just income (Best and Chareunsy, 2022).

Our study also integrates household-level analysis with key area-level variables linked to solar radiation availability. In an ideal world, a place with more solar potential could have more solar installations. Surprisingly, there is an absence of evidence that more solar radiation available (PVOUT) leads to more solar panel use.

We also note that the selection of 11 developing countries is driven mainly by data availability. We have done our best to cover as many developing countries as possible; however, to the best of our knowledge, corresponding household surveys covering solar energy uptake questions are available only for these 11 countries. Nevertheless, these 11 countries represent a diverse sample of the developing world, covering some of the least developed nations from Asia and Africa. While this limitation may be addressed by future studies, we also note that we control for country differences with many binary variables for provinces.

6. Policy implications and conclusion

Our study has four main policy implications. First, our analysis suggests that there is potential for future studies to focus on Cambodia, in case there are key policy insights to be uncovered. We identify Cambodia as having a low proportion of households with formal bank accounts and a high proportion with solar home systems. This latter point is consistent with solar home systems being identified previously as appropriate for rural Cambodia (Watts et al., 2016). Additionally, the country has a high level of solar radiation (Pandey et al., 2022), there is a high cost of electricity from the grid in rural areas of Cambodia (Phoumin, 2015), and there are fewer energy options available in rural areas (Mika et al., 2021). These points may partly explain why solar technology was used in rural Cambodia as early as 1997 (Sarraf et al., 2013) and why approximately half of off-grid households in rural areas of Cambodia access electricity from solar technology (United Nations Development Programme, 2019). Government and nongovernmental organizations, including the World Bank and the Dutch Development Organization, have also contributed substantially (Zhang et al., 2020). Loan availability and education campaigns have also benefited rural areas of Cambodia (Zhang et al., 2020). Further analysis of Cambodia could be useful given that there are zero studies on Cambodia in the meta-analysis by Best et al. (2023).

The second policy implication is that the robust relationships between asset variables and solar uptake align with our study across the diverse range of countries included but noting the different situation in Cambodia. Generally, robust links from assets to solar panel uptake suggest that policies to support households with lower levels of assets can be particularly relevant for policymakers to consider. This could be a novel approach that addresses the key upfront cost constraint in many developing countries.

A third policy implication also follows from the evidence of important upfront cost constraints. Given that these constraints are likely to remain challenging in the future, new approaches might be worth trying. There are many interesting instruments that can pursue the fair and efficient uptake of solar panels and other household technologies (Sterner et al., 2024). One example is an equitable reverse auction where households bid for government support (Best, 2023b; Sterner et al., 2024). Energy auctions have recently become much more common in developing countries, although thus far, this has not extended to the

Table 6
Determinants of adoption of Solar Home System (SHS) including adjustment for solar availability.

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	Solar Home system	Solar Home system	Solar Home system	Solar Home system	Solar Home system	Solar Home system
National PV Practical Potential	−0.5443***					
	(0.0000)					
National PV Cost of energy		−8.3541***				
		(0.0000)				
Province PV Practical Potential			−0.0248		0.0689	
			(0.7744)		(0.5639)	
Province PV Cost of energy				−1.1026		−7.9678
				(0.7531)		(0.1169)
Demographic	Yes	Yes	Yes	Yes	Yes	Yes
Grid	Yes	Yes	Yes	Yes	Yes	Yes
Country dummies	No	No	Yes	Yes	Yes	Yes
Income	No	No	No	No	Yes	Yes
Observations	36,653	36,653	36,653	36,653	22,409	22,409
Adjusted R2	0.124	0.116	0.322	0.322	0.300	0.300

Probit regression results for the impact of the practical PV potential and the cost of energy on the solar system use. Controls not shown for clarity. p values in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 7
Determinants of adoption of each solar device.

	(1)	(2)	(3)	(4)
Variables	Solar_house_system	Light_system	Solar_Lantern	Solar_Batery
Rural dwelling	0.0972**	0.1666***	0.0852**	0.1448*
	(0.0165)	(0.0000)	(0.0117)	(0.0618)
Account; formal	0.4000***	0.2367***	0.1913***	−0.0087
	(0.0000)	(0.0000)	(0.0000)	(0.9153)
Account; informal	−0.0057	0.1164***	0.1173***	0.0861
	(0.8977)	(0.0001)	(0.0007)	(0.2926)
Mobile banking	0.4019***	0.4366***	0.2474***	0.3981***
	(0.0000)	(0.0000)	(0.0000)	(0.0006)
Top Value Land	0.2211***	0.0905***	0.1076***	0.0534
	(0.0000)	(0.0089)	(0.0092)	(0.5310)
Owner of dwelling	0.3109***	0.1183**	0.0798*	0.1506
	(0.0000)	(0.0481)	(0.0725)	(0.3295)
Free of rent	0.2356**	−0.1129	−0.0804	−0.0352
	(0.0157)	(0.2385)	(0.2786)	(0.8592)
Dwelling: Single house occupied by one household	−0.0171	0.1676***	0.2170***	0.3309***
	(0.7279)	(0.0000)	(0.0000)	(0.0038)
Dwelling: Group of enclosed dwellings occupied by one household	0.0077	0.1888**	0.2421***	0.4170***
	(0.9323)	(0.0219)	(0.0007)	(0.0084)
Walls Material: adobe	−0.1938***	−0.0945**	0.0038	−0.2756***
	(0.0000)	(0.0168)	(0.9208)	(0.0001)
Household size	0.0316***	0.0249***	0.0239***	0.0278**
	(0.0000)	(0.0000)	(0.0000)	(0.0339)
Grid: Connected	−1.1653***	−0.9079***	−0.5816***	−1.5111***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Grid: Unconnected, Installation too expensive	−0.3939***	−0.2286***	−0.2339***	−0.3137***
	(0.0000)	(0.0000)	(0.0000)	(0.0001)
Grid: Unconnected, Other reason	−0.0586	−0.0202	−0.0207	−0.1631**
	(0.1913)	(0.6216)	(0.6092)	(0.0308)
Constant	−2.7880***	−3.0151***	−2.3174***	−2.9368***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Province dummies	Yes	Yes	Yes	Yes
Observations	31,275	30,534	32,323	14,789
Overall R-Square	0.384	0.295	0.205	0.322

Probit regression results for four different solar types (solar home systems, solar lighting systems, solar lights, and solar batteries). p values in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

household level (Backer et al., 2023).

The fourth policy implication is that our exploratory analysis of area-level variables suggests the potential for greater efforts to boost solar panel uptake in areas with greater levels of solar radiation. National governments could consider this issue along with the World Bank, which has provided support for prior programs targeting greater solar panel adoption in low-income countries. There is a precedent for this type of extra support for sunnier regions, in the case of Australia. The Small-scale Renewable Energy Scheme provides four levels of support within Australia, with sunnier regions attracting greater support, all else being equal. This scheme has had some success (Best et al., 2019).

This paper fills some gaps in the literature concerning the limited evidence on the determinants of solar energy for developing countries while addressing the usual data limitations in those economies. For example, although the sample contains only 11 countries, this study covers the most developing countries of any household-level solar uptake study, to the best of our knowledge. However, as the MTF survey expands their study, there are many other developing countries that could also be included in the future. A further limitation is the differences in variables between country surveys. We partly overcame this by

Table 8
Probit results with extra socio-economic variables.

Variables	(1) Full Sample	(2) Unconnected only
Rural dwelling	0.3774***	0.3618***
	(0.0000)	(0.0001)
Account in Formal banking	0.3702***	0.4134***
	(0.0000)	(0.0000)
Account in Informal banking	−0.0676	−0.1364*
	(0.2449)	(0.0688)
Mobile banking	0.4072***	0.4192***
	(0.0000)	(0.0000)
Top Value Land	0.1058*	0.2704***
	(0.0669)	(0.0008)
Owner of dwelling	0.1551*	0.1997
	(0.0760)	(0.2291)
Free of rent	0.0415	0.1602
	(0.7503)	(0.4494)
Dwelling: Single house occupied by one household	0.0251	0.0423
	(0.6754)	(0.6226)
Dwelling: Group of dwellings, 1 household	0.0430	−0.0365
	(0.6736)	(0.7746)
Walls Material: adobe	−0.2337***	−0.2680***
	(0.0000)	(0.0001)
Household size	0.0208**	0.0299**
	(0.0216)	(0.0163)
Grid: Connected	−1.1613***	
	(0.0000)	
Grid: Unconnected, Installation too expensive	−0.4253***	−0.4380***
	(0.0000)	(0.0000)
Grid: Unconnected, Other reason	−0.1500***	−0.1549**
	(0.0070)	(0.0101)
Number of rooms	0.0347***	0.0715***
	(0.0012)	(0.0001)
Lower income	−0.0202	−0.0456
	(0.7332)	(0.5342)
Higher income	0.0765	0.1646***
	(0.1289)	(0.0097)
Self employment	0.0351	0.0504
	(0.4103)	(0.3704)
HH female	0.0239	0.0836
	(0.7102)	(0.3781)
Married	0.1265*	0.1441
	(0.0691)	(0.1470)
HH attended School	0.1409***	0.1605**
	(0.0070)	(0.0124)
HH Age	0.0020	0.0045**
	(0.1945)	(0.0246)
Constant	−2.8124***	−3.5060***
	(0.0000)	(0.0000)
Observations	14,259	5777
Overall R-Square	0.398	0.400

Probit regression results for solar home system use, with an additional set of demographic characteristics, including grid access. p values in parentheses. Column 1 contains the complete sample, and Column 2 contains only those unconnected to the grid. p values in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

aligning coding and combining similar variables. However, some variables are unavailable for some countries, or there are intrinsic characteristics of such differences that could not be included, such as differences in administrative duties between countries. While our province binary variables capture provincial differences such as grid reliability, comprehensive data on grid reliability at the household level could add further insights.

Another limitation is that causal inferences are not plausible in some cases, such as our exploratory results using national-level solar radiation in a cross-sectional context. However, we do show that a significant coefficient for solar radiation becomes insignificant with more detailed controls. This provides an example of ruling out a strong positive influence of solar radiation on solar panel uptake in our developing country sample in the established traditional methodology described by Spector (2019). Our analysis provides an important and prior complement to policy formulation, which is based on the extensive number of variables explored in the paper.

Future research can build on our contribution of expanding research coverage for solar adoption in developing countries. Actual household-level data have great potential to add to the more common context of studies of intentions for some prior developing country studies. Longitudinal datasets with detailed information on the timing and reasons for solar adoption will be useful for causal analysis, with subsequent policy implications for targeted intervention programs. This intervention will provide real-life valuable support to households that are currently disenfranchised from solar energy.

CRediT authorship contribution statement

Daniel Mahn: Writing – review & editing, Writing – original draft, Software, Investigation, Formal analysis, Data curation, Conceptualization. **Rohan Best:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Cong Wang:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Olukorede Abiona:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis.

Data availability

Solar availability large image files are available from the following website: https://solargis.com/

The R scripts for extracting province and country solar data are available as Supplementary material.

Solar use microdata data are available following successful registration from the following website: https://microdata.worldbank.org

The Stata code for merging all datasets, building the set of recorded variables and all regression scripts are available in the Supplementary material.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2024.107815.

References

Aarakit, S.M., Ntayi, J.M., Wasswa, F., Buyinza, F., Adaramola, M.S., Ssennono, V.F., 2022. The role of financial inclusion in adoption of solar photovoltaic systems: a case of Uganda. Renew. Energy 198, 984–998. https://doi.org/10.1016/j.renene.2022.08.056.

Abdeladim, Kamel, Razagui, Abdelhak, Semaoui, Smail, Arab, Amar Hadj, 2020. Updating Algerian solar atlas using MEERA-2 data source. Energy Rep. 6, 281–287.

Ajzen, I., 1991. The theory of planned behavior. In: Organizational Behavior and Human Decision Processes, 50, pp. 179–211.

Aklin, M., Bayer, P., Harish, S.P., Urpelainen, J., 2018a. Economics of household technology adoption in developing countries: evidence from solar technology adoption in rural India. Energy Econ. 72, 35–46. https://doi.org/10.1016/J.ENECO.2018.02.011.

Aklin, M., Cheng, C.-y., Urpelainen, J., 2018b. Geography, community, household: adoption of distributed solar power across India. Energy Sustain. Developm. 42, 54–63.

Alipour, M., Salim, H., Stewart, R.A., Sahin, O., 2020. Predictors, taxonomy of predictors, and correlations of predictors with the decision behaviour of residential solar photovoltaics adoption: a review. Renew. Sust. Energ. Rev. https://doi.org/10.1016/j.rser.2020.109749.

Asghar, N., Amjad, M.A., Rehman, H., Munir, M., Alhajj, R., 2022. Achieving sustainable development resilience: poverty reduction through affordable access to electricity in developing economies. J. Clean. Prod. 376, 134040. https://doi.org/10.1016/j.jclepro.2022.134040.

Athey, S., Imbens, G.W., 2017. The state of applied econometrics: causality and policy evaluation. J. Econ. Perspect. 31, 3–32. https://doi.org/10.1257/jep.31.2.3.

Backer, M., Keles, D., Bergaentzlé, C., 2023. Success factors in off-grid energy auctions: a comparative analysis of selected cases from low- and middle-income countries. Renew. Sust. Energ. Rev. 183, 113350.

Bashiri, A., Alizadeh, S.H., 2018. The analysis of demographics, environmental and knowledge factors affecting prospective residential PV system adoption: a study in Tehran. Renew. Sust. Energ. Rev. 81, 3131–3139.

Bass, F.M., 1969. A new product growth for model consumer durables. Manag. Sci. 15 (5), 215–227 http://www.jstor.org/stable/2628128.

Bayer, P., Urpelainen, J., 2016. It is all about political incentives: democracy and the renewable feed-in Tariff. J. Polit. 78 (2), 603–619. https://doi.org/10.1086/684791.

Best, R., 2023a. Assets power solar and battery uptake in Kenya. Energy Econ. 123 https://doi.org/10.1016/j.eneco.2023.106723.

Best, R., 2023b. Equitable reverse auctions supporting household energy investments. Energy Policy 177, 113548.

Best, R., Chareunsy, A., 2022. The impact of income on household solar panel uptake: exploring diverse results using Australian data. Energy Econ. 112, 106124 https://doi.org/10.1016/j.eneco.2022.106124.

Best, R., Burke, P.J., Nishitateno, S., 2019. Evaluating the effectiveness of Australia's Small-scale Renewable Energy Scheme for rooftop solar. Energy Econ. 84, 104475.

Best, R., Marrone, M., Linnenluecke, M., 2023. Meta-analysis of the role of equity dimensions in household solar panel adoption. Ecol. Econ. 206, 107754.

Brent, A.C., Hinkley, James Jim, Burmester, Daniel, Rayudu, Ramesh, 2020. Solar Atlas of New Zealand from satellite imagery. J. R. Soc. N. Z. 50 (4), 572–583.

Chauvin, J.P., Glaeser, E., Ma, Y., Tobio, K., 2017. What is different about urbanization in rich and poor countries? Cities in Brazil, China, India and the United States. J. Urban Econ. 98, 17–49.

de Freitas, B.M.R., 2022. What's driving solar energy adoption in Brazil? Exploring settlement patterns of place and space. Energy Res. Soc. Sci. 89 https://doi.org/10.1016/j.erss.2022.102660.

Dingel, J.I., Miscio, A., Davis, D.R., 2021. Cities, lights, and skills in developing economies. J. Urban Econ. 125, 103174.

Dubey, S., Adovor, E., Rysankova, D., Portale, E., Koo, B., 2019. Kenya Beyond Connections: access to electricity and clean cooking in Kenya based on the Multitier Framework survey and data analysis. ESMAP. https://doi.org/10.1596/24368.

ESMAP, 2020. Global Photovoltaic Power Potential by Country. Washington, DC.

Green, W.H., 2018. Econometric Analysis, 8th ed. Pearson, New York, NY.

Guta, D.D., 2018. Determinants of household adoption of solar energy technology in rural Ethiopia. J. Clean. Prod. 204, 193–204. https://doi.org/10.1016/j.jclepro.2018.09.016.

Hainmueller, J., 2012. Entropy balancing for causal effects: a multivariate reweighting method to produce balanced samples in observational studies. Polit. Anal. 20, 25–46. https://doi.org/10.1093/pan/mpr025.

Hainmueller, J., Xu, Y., 2013. Ebalance: a stata package for entropy balancing. J. Stat. Softw. 54 https://doi.org/10.18637/jss.v054.i07.

International Energy Agency, 2022. World Energy Outlook 2022.

Irfan, M., Yadav, S., Shaw, K., 2021. The adoption of solar photovoltaic technology among Indian households: examining the influence of entrepreneurship. Technol. Forecast. Soc. Chang. 169 (April), 120815 https://doi.org/10.1016/j.techfore.2021.120815.

Jayaweera, N., Jayasinghe, C.L., Weerasinghe, S.N., 2018. Local factors affecting the spatial diffusion of residential photovoltaic adoption in Sri Lanka. Energy Policy 119, 59–67. https://doi.org/10.1016/j.enpol.2018.04.017.

Jedwab, R., Loungani, P., Yezer, A., 2021. Comparing cities in developed and developing countries: Population, land area, building height and crowding. Reg. Sci. Urban Econ. 86, 103609.

Keller, W., 2002. Geographic localization of international technology diffusion. Am. Econ. Rev. 92, 120–142.

Kurata, M., Matsui, N., Ikemoto, Y., Tsuboi, H., 2018. Do determinants of adopting solar home systems differ between households and micro-enterprises? Evidence from rural Bangladesh. Renew. Energy 129, 309–316. https://doi.org/10.1016/j.renene.2018.06.015.

Kwan, C.L., 2012. Influence of local environmental, social, economic and political variables on the spatial distribution of residential solar PV arrays across the United States. Energy Policy 47 (C), 332–344.

Lay, J., Ondraczek, J., Stoever, J., 2013. Renewables in the energy transition: evidence on solar home systems and lighting fuel choice in Kenya. Energy Econ. 40, 350–359. https://doi.org/10.1016/j.eneco.2013.07.024.

Lin, F., Wang, R., Feng, K., 2023. Regional favouritism in Chinese university admissions. Econom. Trans. Institut. Change. https://doi.org/10.1111/ecot.12385.

Liu, D., Qi, S., Xu, T., 2023. Visual observation or oral communication? The effect of social learning on solar photovoltaic adoption intention in rural China. Energy Res. Soc. Sci. 97 https://doi.org/10.1016/j.erss.2023.102950.

Mika, K., et al., 2021. Situation analysis of energy use and consumption in Cambodia: household access to energy. Environ. Dev. Sustain. 23, 18631–18655.

Pandey, A., et al., 2022. Solar energy utilization techniques, policies, potentials, progresses, challenges and recommendations in ASEAN countries. Sustainability 14, 11193.

Phoumin, H., 2015. Renewable energy policies and the solar home system in Cambodia. ERIA Discus. Paper Ser. 2015–2064.

Poblete-Cazenave, Miguel, Pachauri, Shonali, 2021. A model of energy poverty and access: estimating household electricity demand and appliance ownership. Energy Econ. 98, 105266. https://doi.org/10.1016/j.eneco.2021.105266.

Rahut, D.B., Mottaleb, K.A., Ali, A., Aryal, J., 2018. The use and determinants of solar energy by Sub-Saharan African households. Int. J. Sustain. Energy 37 (8), 718–735. https://doi.org/10.1080/14786451.2017.1323897.

Rehman, I.H., Malhotra, P., Pal, R.C., Singh, P.B., 2005. Availability of kerosene to rural households: a case study from India. Energy Policy 33 (17), 2165–2174.

Rogers, E., 2003. Diffusion of innovations (5th Edition). Simon and Schuster.

Sarraf, M., Rismanchi, B., Saidur, R., Ping, H.W., Rahim, N.A., 2013. Renewable energy policies for sustainable development in Cambodia. Renew. Sust. Energ. Rev. 22, 223–229.

Shahid, I.A., Ullah, K., Miller, C.A., Dawood, M., Ahmed, M.I., 2022. Rooftop solar adoption among populations and markets outside the US and Europe–a case from Pakistan. Electr. J. 35, 107090.

Shahsavari, A., Akbari, M., 2018. Potential of solar energy in developing countries for reducing energy-related emissions. Renew. Sust. Energ. Rev. https://doi.org/10.1016/j.rser.2018.03.065.

Smith, M.G., Urpelainen, J., 2014. Early adopters of solar panels in developing countries: evidence from Tanzania. Rev. Policy Res. 31 (1), 17–37. https://doi.org/10.1111/ropr.12061.

Sørensen, J.F., 2016. Rural–urban differences in bonding and bridging social capital. Reg. Stud. 50 (3), 391–410.

Spector, P., 2019. Do not cross me: optimizing the use of cross-sectional designs. J. Bus. Psychol. 34, 125–137.

Sterner, T., Ewald, J., Sterner, E., 2024. Economists and the climate. J. Behav. Exp. Econom. 109, 102158.

United Nations Development Programme, 2019. Harnessing the Solar Energy Potential in Cambodia.

United Nations: Department of Economic and Social Affairs, 2022. The Sustainable Development Goals Report 2022.

van Benthem, A.A., 2015. Energy leapfrogging. J. Assoc. Environ. Resour. Econ. 2, 93–132.

Wang, X., Zheng, Y., Jiang, Z., Tao, Z., 2021. Influence mechanism of subsidy policy on household photovoltaic purchase intention under an urban-rural divide in China. Energy 220. https://doi.org/10.1016/j.energy.2020.119750.

Watts, R., Smith, J., Thomson, A., 2016. The design and installation of solar home systems in rural Cambodia. J. Human. Eng. 4 (2), 16–23.

Zaman, R., Borsky, S., 2021. The impact of supply structure on solar home system installations in rural off-grid areas. Environmental Innovation and Societal Transitions 40, 625–644.

Zhang, J., Raufer, R., Liu, L., 2020. Solar home systems for clean cooking: a cost–health benefit analysis of lower-middle-income countries in Southeast Asia. Sustainability 12, 3909.