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RESEARCH ARTICLE

Impact of Off-Grid Solar Home Systems on Energy Spending in Oyo State, Nigeria

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Abstract: Energy insecurity in the developing nation of Nigeria has driven communities and households in both rural and urban areas to adopt solar home systems (SHS) as a source of household energy. A report published by Fraym® is used by the Rural Electrification Agency (REA) for Nigeria Electrification Project (NEP) to develop its Energy Transition Plan for 100% electrification. It focuses on 10 Nigerian states, and points to customer profiles for top off-grid communities from these states. This report reveals the top twenty communities with the highest propensity to adopt SHS. The concentration of the top fifty solar home system communities is particularly significant among these communities, covering approximately 570,000 households in Oyo State. This unique positioning makes Oyo State an ideal focal point for conducting an empirical analysis. Conducting a cross-sectional empirical analysis in Omiyale, Madeko, Saki, and Ibadan, the study employs a stratified random sampling approach, selecting 40 SHS and 40 non-SHS households. The findings underscore the overall efficacy of off-grid SHS in addressing energy poverty. SHS owners exhibit a substantial improvement in lighting usage, marked by a notable shift towards cleaner and sustainable energy sources. Notably, SHS ownership correlates with a positive economic impact, as monthly expenditures for energy among SHS households decrease by an average of 1287.308 Naira per month. This economic saving stems from reduced reliance on conventional energy sources like candles, kerosene, and batteries.

Keywords: CO_2 emission saving, ordinary least square OLS, payback period, regression analysis, solar home system, spending

1. Introduction

1.1. Energy consumption patterns in Nigeria

Nigeria's aggregate installed power generation capacity currently stands at 16,384 MW. The primary sources of power generation are hydro and gas-fired thermal power plants, contributing 2,062 MW and 11,972 MW, respectively. The remaining power supply, amounting to 2,350 MW, is derived from sources such as solar, wind, diesel, and heavy fuel oil [1].

85% of Nigerians lack access to reliable electricity [2]. The efforts to extend electricity to all corners of Nigeria have been strained by unavailable and, in some cases, idle infrastructure, characterized by outdated and inadequate power grids. With limited access to unreliable on-grid electricity, the population relies on off-grid solutions, the most common being small-scale diesel and petrol generators, especially in urban and semi-urban areas. The Rural Electrification Agency of Nigeria aims to replace diesel generators in such clusters with better options, particularly to provide electricity to support the growth of micro, small, and medium enterprises [3].

Elinwa et al. [4] revealed the average monthly consumption of electricity from Utility Companies to be 156.56 kWh, 229.58 kWh, and 319.41 kWh for small-, medium-, and large-sized houses, respectively. The same housing units went with generators to compensate for insufficient and irregular power supply and consumed 273.75 kWh, 698 kWh, and 1530 kWh monthly. This future adds to highlighting disappointing levels of power generation and distribution through the National Grid system and heavy reliance on petrol and diesel generators.

Weak policies and regulatory framework implementation have also acted as stumbling blocks on the path to complete electrification. Inconsistent governance, a lack of clear guidelines, and a dearth of incentives for private investment have stunted the growth of a robust energy sector. Without comprehensive policies, the dynamics of energy generation, distribution, and consumption remain fragmented and unable to foster the transformative changes needed.

These challenges, intertwined and formidable, have collectively contributed to Nigeria falling short of attaining the coveted 100% electrification goal. This predicament has ignited an intense exploration of alternative avenues, propelling off-grid solutions like solar home systems into the limelight.

The paper is structured to provide a comprehensive analysis of the impact of off-grid solar home systems on energy spending in Oyo State, Nigeria. It begins with an Introduction that outlines Nigeria's energy consumption patterns, the challenges of achieving full electrification, and the potential of SHS. The Literature Review discusses previous studies on the social and economic impacts of SHS in various regions, emphasizing the need for localized research in Oyo State. The Research Methodology section details the research design, data collection methods, and analytical techniques used in the study. Further, the results section presents the findings from the empirical analysis, including the impact of SHS on energy consumption, payback time calculation, and saving on CO_2 emissions. The discussion interprets these results, comparing them with findings from other regions and discussing

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broader implications for energy policy and economic development. The conclusion section summarizes the key findings, their significance, and provides recommendations for future research and policy initiatives. Finally, the references section lists the sources cited throughout the paper, providing a comprehensive bibliography for further reading.

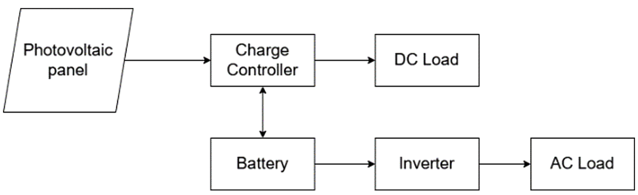
1.2. Off-grid solar home system

Off-grid solar home systems represent decentralized and autonomous power generation configurations that leverage photovoltaic technology to furnish electricity to all its users, especially to populations situated beyond conventional centralized power distribution networks.

Modularity is a defining characteristic of off-grid SHS, enabling tailoring to the unique energy requirements of individual households or establishments. These systems possess the capacity to energize an array of equipment and gadgets, spanning lighting, communication tools, cooling units, fans, household electronics like TV, radio, electric sewing machine, and even modest machinery like milling and sanding tools. In certain setups, energy-conserving devices and LED lights are integrated to maximize energy efficiency.

Off-grid solar configurations tap into solar irradiance, an inexhaustible and renewable energy resource, to initiate electricity generation. Photovoltaic panels, housing semiconductor photovoltaic cells, trigger the photovoltaic effect, transforming incident sunlight into electrical energy in the form of DC power. Subsequently, power inverters convert DC power into AC power, which aligns with the standards of conventional household electrical appliances. Figure 1 shows the block diagram of off-grid solar home systems.

Figure 1
Block diagram of off-grid solar home system



In 2019, Nigeria's solar energy capacity reached approximately 18.67 megawatts or 28 GWh. This figure represents a decent surge compared to the capacity in 2012 of merely 15 megawatts [5]. However, the calculated potential for concentrated solar power and photovoltaic generation across the country is around 427,000 MW [6]. The market for minigrids and solar home systems in Nigeria is substantial, with significant potential for cost savings of billions annually for households and businesses [7]. When implemented strategically, this can easily solve the nation's present and future energy demand.

2. Literature Review

A comprehensive analysis of the social benefits of clean energy in rural Bangladesh was conducted with specifically focusing on the economic, employment, environmental, educational, and health outcomes resulting from the adoption of solar home systems. Employing ordinary least squares and propensity score matching techniques, the study revealed a considerable reduction in kerosene consumption as an indicator of effective electricity utilization through SHS. The analysis also highlighted an increase in income and higher expenditure among SHS adopters compared to non-adopters. The research discussed in detail that the adoption of off-grid solar home systems has not only provided for necessities like lighting during after-hours but has also empowered individuals with access to essential electronics such as mobile phones and radios. This connectivity has opened doors to better communication, information dissemination, and opportunities for the local communities thereby increasing the energy utilization and therefore spending [8]. While the study provided valuable insights, a limitation was noted in its focus on rural zones, thereby not presenting a comprehensive picture of SHS adoption impacts in the broader region.

A detailed empirical study on the adoption of solar home systems through government initiatives in India concludes that decentralized energy solutions, by means of solar home systems, have seen a rise through the government's various electrification initiatives, especially in the rural zones. Research on adoption of solar home systems through government initiatives in India. It was concluded through detailed empirical study that decentralized energy solutions through means of solar home systems have seen a rise through the government's various electrification initiatives especially in the rural zones. Achievements of installations of solar home lights under the JNNSM scheme have seen an exponential increase starting from 2010 with a combined 1,7 million beneficiaries. The same research states that the availability of electricity for recreational electronics like televisions has brought about a shift in leisure activities, impacting the way people spend their leisure time and providing an alternative form of entertainment for families. This has influenced social dynamics and family interactions in the region. With many households now having access to off-grid electricity, there are changes in how they utilize energy for daily activities, leading to a shift in overall energy consumption patterns. The rise of off-grid solar systems has had economic ramifications, affecting household spending. With reduced dependency on expensive and unreliable sources of energy, families have experienced changes in their monthly expenditures. Such cases bring in the point of upliftment of people from no electricity to electrification, implying energy poverty reduction to a considerable extent [9].

In a study aimed to explore the socio-economic impacts of off-grid systems in rural southwest Nigeria, the investigation included a survey of 83 micro and small enterprises, with a focus on variables such as gender, marital status, household size, age, education level, years of business establishment, hours of operation, building tenure, capital source, number of employees, generator ownership, and the days of operation [10]. The study found 6 out of the 12 predictors, namely female gender, household size, year of business establishment, building tenure, owning generator previously, and number of employees appeared to have a significant influence on the average income of the mini-grid users. SHS households score high on the number of business enterprises created, employment statistics, energy expenses, and income generated.

An investigation aimed to assess the economic viability of off-grid solar systems for the Nigerian private sector utilized load profiles from six industrial sectors, namely real estate, education, banking, automobile, hospitality, and production, to calculate the levelized cost of electricity using solar and hybrid diesel energy systems. 40 responses were received, with more than 90% of which were from private companies from Lagos and Ogun states. HOMER Pro 3.12.5 was used to model the energy system for each of 6 sectors. The findings indicated a lower cost of electricity with the inclusion of solar PV and even lower with the coupling of storage batteries. In five out of the six sectors, the PV systems had payback times of less than a year and return on investments exceeding 100% [11].

Empirical analysis conducted using data from the 2015 living standard measurement survey of Ivory Coast also shows that solar home system promotes entrepreneurship in off-grid areas. The empirical strategy included a Binary Probit Model, used to estimate the probability of being an entrepreneur, and a Multivariate Probit Model, used to analyze the probability of engaging in entrepreneurship across different sectors such as agriculture, trade, industry, and services. Additionally, an endogeneity test was conducted to check if the adoption of SHS is endogenous to the entrepreneurship decision. Among the few solar home system adopters who use their systems for business purposes, there has been a positive impact on micro firm creation. Access to SHS increases the probability of engaging in entrepreneurial activities by 6.5 percentage points [12].

The South African SHS case concludes SHS-generated illumination exerts a favorable influence on households, facilitating improved access to information, entertainment, and potential educational benefits for children. Evaluating the direct economic effects of SHS proved challenging due to a dearth of verifiable evidence to the researchers. However, peripheral economic and social impacts were seen arising from secondary SHS electricity use, notably supporting nighttime business activities [13].

Literature review above guides in understanding strides made in the developing world due to implementation of SHSs. There is a holistic discussion of studies from diverse regions such as Bangladesh, India, Nigeria, Ivory Coast, and South Africa, the absence of specific studies focused on Nigeria, especially Oyo State, is notable. This gap highlights the need for more localized research to understand the nuances of off-grid solar system impacts on energy spending in Oyo State, thereby painting a picture for Nigeria.

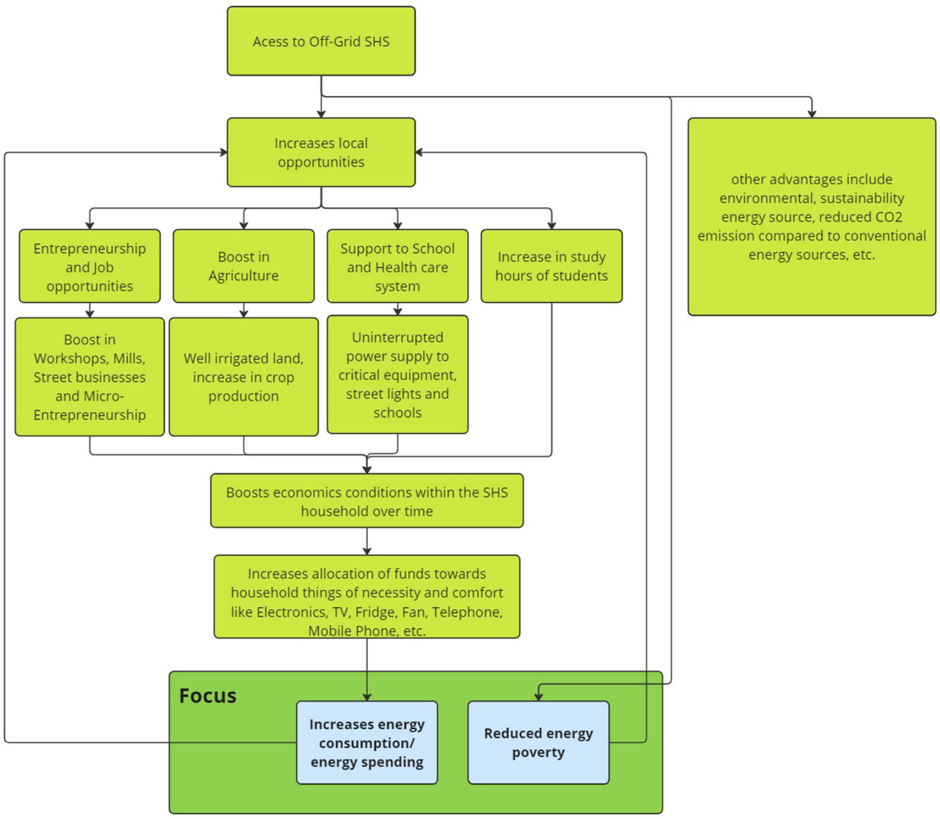
The research title pertains to Oyo State, and the current research lacks a focus in addressing the energy spending dynamics in this specific region. Willingness to adopt SHS is lower in high-income neighborhood than low-income one [14]. A substantial portion of Oyo's population (42%) lives below poverty line [15], increasing Oyo's propensity for households' ownership of SHS.

Author's intention for this study is to bring a new look to the existing literature in the areas of providing through OLS regression methods, a measurable impact of SHS in key peri-urban communities within Oyo, Nigeria, a West African country. It provides for the first time, through a comprehensive customer profile database and survey questionnaire, SHS adoption patterns and energy consumption behaviors, investigating how SHS adoption affects monthly energy expenditures. The study also calculates CO_2 emissions for the expected operational life cycle of the SHS.

2.1. Conceptual framework

Results of preliminary research are used to create a flow chart or sequence in which access to SHS tackles issues related to energy poverty, effect on local economy, and energy spending. The more cost-effective an energy solution is the greater is its tendency in reducing energy poverty. The flowchart guides into the topics to dive in for detailed empirical review. Figure 2 shows the conceptual framework, relation between energy access and energy poverty, effect on local economy, and energy spending.

Figure 2
Conceptual framework, relation between energy access and energy poverty, effect on local economy, and energy spending



A primary outcome is the transition away from traditional lighting methods due to the introduction of a new energy source. This shift involves moving away from the reliance on kerosene-powered lamps and battery-operated devices, leading to reduced energy-related expenditures. This transition offers a multitude of benefits.

1) Reduced energy expenditure: Kerosene is a notoriously expensive fuel source. Replacing it with solar energy leads to significant cost savings for households, particularly in regions with volatile fuel prices [16]. Studies in Bangladesh have shown a decrease in household energy expenditure by as much as 50% upon SHS adoption [17].
2) Convenience and safety: Kerosene lamps are inconvenient to maintain and pose fire safety risks. SHS eliminates these concerns, providing a safe, reliable source of light that can be readily switched on and off.
3) Improved health: Kerosene lamps emit harmful pollutants, contributing to respiratory illnesses, particularly among children [18]. The transition to clean solar energy fosters a healthier living environment for families.

Furthermore, the availability of electricity is expected to drive a substitution from external mobile phone charging to in-home charging, resulting in saved time, reduced costs, and the potential for generating additional income. This shift away from kerosene usage also carries positive environmental implications, particularly in terms of decreased air pollution and its associated health benefits.

Beyond energy-related changes, the introduction of electricity can potentially reshape how households allocate their time. This could manifest as increased time devoted to income-generating activities, educational pursuits, and leisure activities such as radio listening, TV watching, and mobile phone usage. As time progresses, these changes in how time is spent lead to improved academic achievement, increased understanding of diverse health concerns, fertility issues, gender roles, and social customs [19].

The ecosystem experiences a notable improvement, primarily leading to a decrease in energy poverty. This positive transformation is driven by heightened economic activity, resulting in increased energy expenditures. As the local economy flourishes, there is a potential for a rise in the number of users adopting SHS, and existing SHS users may escalate their energy spending to align with an elevated standard of living. This cyclical effect contributes to an overall upliftment in the community.

Interrelationships between the core concept terminologies stated above serve as a foundational framework for developing comprehensive survey questionnaires by identifying key variables, operationalizing them into measurable indicators, and incorporating direct and indirect questioning techniques. By designing sequential questions that capture the interplay between variables, one can effectively explore the complexities of energy access, energy poverty, and spending.

2.2. Theoretical framework

Statistical operations such as Regression find their application in determination of relation between dependent and independent variables. Multiple linear regression is a statistical method used to model the relationship between a dependent variable and multiple independent variables [20]. It is a generalization of simple linear regression, allowing for the inclusion of more than one explanatory variable. This method can be used to describe relationships, predict future scores, and test specific hypotheses. It is a powerful and flexible tool, particularly suited to problems involving binary-coded information [21].

Particularly in context of this research, each independent variable's coefficient in the regression equation may quantify its impact on energy spending. This can help to identify influential factors, make predictions, and test hypotheses, thereby facilitating informed decision-making and policy formulation for SHS implementation. There are other statistical methods such as structural equation modeling and multivariate analysis of variance that offer similar capabilities for analyzing multivariate data.

Looking at Data sampling technique, stratified random sampling method can be used to ensure that the sample accurately represents the population by dividing it into distinct subgroups or strata based on relevant characteristics such as age, gender, or income level. Within each stratum, random samples are independently selected, making sure a fair share for all subcategories within the sample. By considering the natural variations within the population, this technique produces more precise estimates. Additionally, it can be a more efficient approach than simple random sampling, especially when subgroups within the population differ significantly.

Versatility of stratified random sampling in various research domains can be seen in its application. Research applied this technique to feature subspace selection in random forests for high dimensional data, improving classification performance [22] while other used random sampling for multi-labeled data [23]. A pioneering researcher developed computer software for stratified random site selection in a groundwater-quality sampling network, demonstrating its utility in environmental studies [24]. For a dataset such as SHS and potential SHS owners, it is important to represent unbiasedly both large and small SHS users. Stratified random sampling can help solve this issue.

3. Research Methodology

3.1. Research design

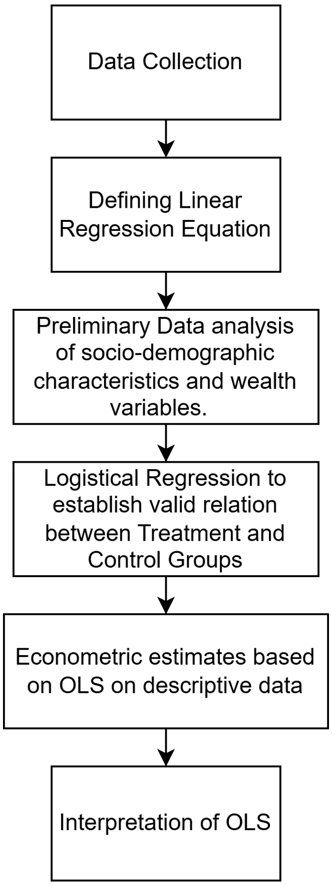
The scientific aim of the work is to determine the overall cost-effectiveness of off-grid SHS, payback period due to the SHS users, and CO_2 emission saving from SHS usage.

This is done as seen in Figure 3 by Data collection. The first component of this analysis involves simple statistical techniques applied to survey data collected from SHS-owning households and prospective SHS owners/households are also referred to as non-SHS owners/households. An overall balance test is further performed on the p-values of socio-demographic characteristics and wealth variables. This critical step involves evaluating the comparability of the datasets on all the variables, ensuring that systematic differences do not skew subsequent analyses to check if the assumed hypothesis needs to be addressed entirely. By rigorously examining the similarity of the datasets, one can increase confidence in the generalizability of findings and the reliability of any identified differences. Kolmogorov-Smirnov test offers a more comprehensive approach to assessing overall balance between groups compared to traditional methods like chi-square and t-tests.

Once a clear ground is established to compare treatment and control groups, OLS is performed on the defined linear regression equation for both treatment and control group using the observed descriptive statistical dataset, and the difference in coefficients of equation is interpreted. Here, OLS regression analyzes the impact of SHS on various outcomes and answers three research questions.

1) How much cost-effective are off-grid SHS, how much is the cost saving for the off-grid SHS users?

Figure 3
Steps of empirical analysis



2) How much of payback period do SHS users realize?
3) How much is the CO_2 emission saving?

Finally, payback time calculations are made to help understand the financial aspect of owning SHS and quantify monthly energy savings compared to non-SHS users and savings on CO_2 emissions are calculated to look at the environmental impact of SHS implementation.

3.2. Participants

The study employs a cross-sectional data collection approach across Omiyale, Madeko, Saki, and Ibadan, strategically targeting rural and peri-urban communities with high SHS ownership propensities within Oyo State.

Utilizing a treatment-control model, the study compares existing and prospective SHS customers, identified through a vendor-furnished KYC database. This database helped consolidate data and analyze existing SHS customer and prospective customer database from singular SHS product-selling firm. A prospective customer is customer or family who has expressed an interest in buying an SHS system in the vendor-furnished KYC database.

The SHS firm offers a diverse range of solar-based products. The most popular products for household application, and thus used for analysis, are an 11 W solar panel with three lights and mobile phone charging, priced at around 56,000 Naira, and a 50 W solar panel with five lights, mobile phone charging, and a 23-inch LED color TV, priced at around 256,000 Naira.

Each product provides approximately 5 h of bright light at its highest settings and outputs between 120 and 150 lumens. Additionally, the firm ensures after-sales services and provides a one-year warranty for all SHS models.

3.3. Sample and sampling technique

The sampling strategy hinges on the assumption that recent SHS adopters share similar unobservable traits with prospective buyers (this assumption is further proved to be true by results of Logistical Regression).

Using a stratified random sampling approach, selection of approximately 40 households that owned SHS from a pool of 122 members possessing an SHS was accomplished. Same procedure was used for selection of 40 prospective households from pool of 110 households across 4 areas. Table 1 shows share of SHS users and prospective SHS users in random sampling.

3.4. Method of data collection

Socioeconomic indicators and household demographics were recorded for treatment and control groups. This detailed dataset has insights on the household head and spouse's characteristics like age, education, sectors of employment, and household characteristics such as size, quality of living space, agricultural land, livestock, ownership of transportation, and assets such as gas stoves, mosquito nets, and electric sewing machines. Table 2 displays the statistical means of both groups.

Table 1
Share of SHS users and prospective SHS users in random sampling

	SHS users	Treatment sample	Prospective SHS users	Control sample
Omiyale				
Home 200X 11W (3 lights)	12	7	16	8
Home 500X 50W (5 lights, TV)	16	3	8	3
Madeko				
Home 200X 11W (3 lights)	23	2	11	5
Home 500X 50W (5 lights, TV)	17	4	9	7
Saki				
Home 200X 11W (3 lights)	6	4	19	4
Home 500X 50W (5 lights, TV)	9	5	4	1
Ibadan				
Home 200X 11W (3 lights)	23	8	23	3
Home 500X 50W (5 lights, TV)	16	7	20	9
Grand Total	122	40	110	40

Table 2
Socio-demographic characteristics and wealth variables

	Treatment mean	Control mean	Difference in means p-value
Household head characteristics			
Age	46.1	46.75	0.056
Head is Female	0.25	0.3	0.016
Schooling (Excluding: No schooling)			
Primary	0.4	0.325	0.592
Secondary or Higher	0.6	0.675	0.592
Occupation (Excluding: Other Occupations)			
Agriculture, hunting, fishing	0.4	0.35	0.793
Retail/sales	0.225	0.325	0.397
Private sector formally employed	0.1	0.2	0.119
Public sector formally employed	0.25	0.15	0.619
Spouse characteristics			
Age	39.6	40	0.353
Spouse is male	0.75	0.725	0.0069
Schooling (Excluding: No schooling)			
Primary	0.725	0.625	0.261
Secondary or Higher	0.55	0.35	0.399
Occupation (Excluding: Other Occupations)			
Agriculture, hunting, fishing	0.425	0.275	0.355
Retail/sales	0.25	0.275	0.319
Private sector formally employed	0.125	0.175	0.878
Public sector formally employed	0.175	0.3	0.426
Household characteristics			
Respondent is head	0.225	0.275	0.002
Household size	6.35	6.325	0.052
Quality of the main building			
Floor is made of cement/ brick/ ceramic	0.5	0.575	0.025
Walls			
Walls are made of cement	0.325	0.225	0.953
Walls are made of bricks	0.5	0.425	0.756
Roofing: Iron Sheets	0.4	0.4	0.701
Glass windows	0.575	0.525	0.228
No. of rooms for living	3.575	3.65	0.993
Agricultural land			
Acres owned	3.125	2.7	0.734
Acres cultivated	1.4	1.725	0.96
Livestock			
Number of cows	2.125	1.8	0.39
Number of sheep	1.425	1.825	0.591
Number of goats	1.175	1.5	0.813
Ownership: Means of transportation			
Bicycle	0.35	0.35	0.946
Motorcycle	0.425	0.35	0.041
Car	0.375	0.325	0.003
Assets			
Gas stove	0.725	0.75	0.843
Mosquito nets	0.4	0.475	0.802
Mechanical Sewing machine	0.225	0.1	0.902
Overall balance test			**0.144**

Balanced groups increase the likelihood that any observed difference in the outcome between the control and treatment groups is truly due to the treatment itself, not pre-existing differences between the groups. To prove this, the Kolmogorov-Smirnov test was carried to assess the overall balance of the means between the control and treatment groups. It is a non-parametric statistical method designed to assess the goodness-of-fit between two probability distributions. Specifically, it evaluates whether a given set of p-values deviates significantly from a uniform distribution, a fundamental assumption in many statistical analyses.

The Kolmogorov-Smirnov test yielded a statistic of 0.144. A significance level of 0.05 indicates a very low probability (only 5%) of observing such a difference. Additionally, with a moderate sample size of 40 per group, the Kolmogorov-Smirnov test becomes more potent in detecting meaningful discrepancies. These factors combined provide statistically significant evidence that the distributions of means in the control and treatment groups are similar. This suggests a strong likelihood that both groups started with comparable average values, enhancing the validity of our subsequent analysis, and strengthening the foundation for concluding the treatment effect.

To further examine the similarities and differences between the two groups in the likelihood of owning a SHS, a series of logit models were estimated. The dataset is divided into two groups: treatment and control. For each group, the code constructs a logistic regression model to predict the probability of the outcome occurring given the treatment status. The core of the model is the sigmoid function, which maps any real number to a value between 0 and 1, interpretable as a probability. The model parameters, represented by theta, are estimated using gradient descent, an iterative optimization algorithm that minimizes the difference between predicted and observed outcomes. The gradient descent algorithm calculates the gradient of the cost function with respect to the parameters and updates the parameters in the direction of steepest descent. The process continues iteratively until convergence. Once the models for both treatment and control groups are fitted, the resulting parameter estimates can be compared to assess the impact of the treatment on the outcome. A positive coefficient for the treatment variable in the treatment group model, relative to the control group model, suggests a positive association between the treatment and the outcome.

As seen in Table 3, the majority of observable characteristics show little influence on the probability of owning a SHS.

Table 3
Logistic regression estimates for the probability of owning a SHS (range of 0 to 1, 0.5 suggests no significance of parameter of SHS ownership)

	Logistic regression estimates for the probability of owning a SHS
Respondent is head	0.457
Household size	0.689
PPI score	0.520
Quality of the main building	
Floor made of cement/brick/ceramic	0.411
Walls	
Walls are made of cement	0.590
Walls are made of bricks	0.450
Roofing: Iron Sheets	0.495
Glass windows	0.492
No. of rooms for living	0.402
Agricultural	
Acres owned	0.511
Acres cultivated	0.389
Livestock	
Number of cows	0.399
Number of sheep	0.671
Number of goats	0.550
Means of transportation	
Bicycle	0.445
Motorcycle	0.398
Car	0.511
Assets	
Gas stove	0.612
Mosquito nets	0.459
Mechanical Sewing machine	0.490
Use of the national grid in past 5 years	0.592

In summary, both the comparison of means and the logit estimates indicate that.

1) the sampling approach has resulted in reasonably comparable groups
2) the disparities in estimated treatment probabilities are minimal, with substantial common support ensuring comparability between treatment and control groups; and
3) the marginal variations in observable characteristics imply that differences in unobserved traits between the two groups are likely not prominent.

3.5. Method of data analysis

The analysis starts with determining the statistical significance of the slope coefficients in a multiple linear regression model. The formula is as Equation (1):

$$Y = \beta_0 + \beta_1 SHS + \beta_2 H + error \tag{1}$$

Here,

Y = outcome of interest (dependent variable) added time of energy consumption/spending
SHS = (independent variable) solar home systems

H = (independent variable) set of observable household characteristics

β_0 is the intercept term while β_1, β_2 are the coefficients associated with *SHS* and *H,* respectively. The term error represents the residual term in the regression equation. The intercept term provides a reference point for the regression equation, and the error term accounts for the unobserved and random components in the relationship between the independent and dependent variables.

To calculate OLS coefficient for treatment and control group, namely Intercept point β_0, Slope β_1, Quadratic coefficient β_2 and error, the following formulas solved using Python programming are as Equations (2)–(5):

$$\beta_1 = \frac{n\sum xy - \sum x \sum y}{n\sum x^2 - \left(\sum x\right)^2} \tag{2}$$

Where:

x = The independent variable. In this analysis, x represents the index or a specific feature based on which the dependent variable y is predicted.

y = The dependent variable. This is the variable that is aimed to be predicted.

n = Number of Data points = 40
$\sum xy$ = Sum of the product of each x and y value.
$\sum x$ = Sum of all x values.
$\sum y$ = Sum of all y values.
$\sum x^2$ = Sum of the squares of each x value.
β_1 represents the change in the dependent variable for a one-unit increase in the independent variable, holding the quadratic term constant.

$$\beta_2 = \frac{n\sum x^2 y - \sum x^3 \sum y}{n\sum x^2 - (\sum x)^2} \tag{3}$$

Where:

$\sum x^2 y$ = Sum of the product of each x^2 and y value.

$\sum x^3$ = Sum of the cubes of each x value.

β_2 captures the curvature of the relationship between the independent and dependent variables.

$$\beta_0 = \frac{\sum y - \beta_1 \sum x - \beta_2 \sum x^2}{n} \tag{4}$$

This formula calculates the intercept of the regression model by adjusting for the contributions of the linear and quadratic terms. Essentially, it represents the predicted value of the dependent variable when the independent variable is zero.

$$Error = \frac{\sum (y_i - (\beta_0 + \beta_1 x_i + \beta_2 {x_i}^2))^2}{n} \tag{5}$$

This formula calculates the mean squared error, which is the average of the squared differences between the observed and predicted y values. It measures the goodness of fit of the model. A lower mean squared error indicates a better fit.

Here,

y_i = The observed y value.

$\beta_0 + \beta_1 x_i + \beta_2 {x_i}^2 =$ The predicted y value from the regression model. Table 4 shows parameters and descriptions.

4. Results

The subsections below display results of OLS synthesis and discussion on effects of SHS, payback time calculation for SHS, and calculation for savings in CO_2 emission.

4.1. Impact of SHS

It is evident from OLS that there is a considerable increase in the usage of LED lamps. LED lamps are used for about 2.77 h or 166 additional minutes per day while there is a corresponding reduction in the combined use of clean and dirty lamps by 61 min. The increased satisfaction with the quality of lighting provided by SHS suggests well-being gains from SHS, which are further supported by changes in energy consumption and usage patterns of different lighting sources. Table 5 shows logistic effect of SHS on lighting.

A less pronounced impact in terms of cost savings is observed for batteries used for radios and candles. The identified total monthly reduction in expenditure on energy for both amounts to around Naira 614.769 among SHS owners than the non-SHS users. SHS owners tend to spend around Naira 515 less on firewood when compared to non-SHS users.

Looking at Table 6, it is seen that a substantial proportion SHS users own a TV, and it is unsurprising to observe a 25-point increase in TV ownership among SHS owners compared to the control group. This ownership translates into heightened TV-watching habits, with SHS owners dedicating approximately 31 more minutes daily in watching TV than the non-SHS users. The primary contributor to this increase is adult female and children of the household. SHS user's spouse watches TV 10.21 min more compared to non-SHS user's spouse. Also, SHS user's children get almost 17 extra minutes of TV viewing when compared to non-SHS user's children. Even house heads, primarily the bread winners, watch additional 10min of TV when compared with non-SHS house heads.

A noteworthy effect of SHS ownership is the heightened likelihood of charging mobile phones for others. On average, SHS owners provide phone charging services about 2.28 times more per week than the non-SHS owners. However, the financial gains from offering such services are modest (Naira 46.615). A more distinct impact is that lesser of SHS-owning users charge their

Table 4
Parameters and descriptions

Parameters	Description
Y	Outcome of interest (dependent variable) added time of energy consumption/spending
SHS	(independent variable) solar home systems
H	(independent variable) set of observable household characteristics
β_0	is the intercept term
β_1, β_2	are the coefficients associated with SHS and H respectively.
$Error$	The term error represents the residual term in the regression equation.
$\beta_0 + \beta_1 x_i + \beta_2 {x_i}^2$	The predicted y value from the regression model
x	The independent variable. In this analysis, x represents the index or a specific feature based on which the dependent variable y is predicted.
y	The dependent variable. This is the variable that is aimed to be predicted.
n	Number of Data points = 40
$\sum xy$	Sum of the product of each x and y value.
$\sum x$	Sum of all x values.
$\sum y$	Sum of all y values.
$\sum x^2 y$	Sum of the product of each x^2 and y value.
$\sum x^3$	Sum of the cubes of each x value.
y_i	The observed y value.

Table 5
Logistic effect of SHS on lighting

	OLS
No. of clean lamps used	−0.215
No. of LED lamps used	2.026
No. of dirty lamps used	−0.634
Daily use hours: Clean lamps	0.25
Daily use hours: LED Lamps	2.77
Daily use hours: Dirty lamps	−1.265
Satisfaction with lighting	2.33(out of 5)

Table 6
Effect of SHS on daily TV consumption

	OLS
Ownership of TV	0.253
Minutes TV is turned on per day	30.711
Head: Minutes watching TV per day	9.98
Spouse: Minutes watching TV per day	10.211
Children: Minutes watching TV per day	16.903
Times mobile charged for others	2.28
Weekly income of phone charging	46.615
Weekly costs of phone charging	−31.5

phones outside their home. In terms of costs, this translates to a reduction in phone charging expenses of around Naira 31.5 per week. Interestingly, the entrepreneurial behavior of phone charging as a service is found to be a common practice in Oyo State and parts of Bangladesh as seen in research by Kabir et al. [25].

Use of kerosene for lighting is significantly less compared to non-SHS users. With 8 liters (0.66 ml per month) of kerosene annually saved compared to non-SHS users on lighting during dark hours, SHS houses in Oyo communities are significantly reducing indoor pollution and bettering household's health. These results echo similarities with research from all around the globe, especially Makol et al. [9] who used OLS to deduct concrete relation between SHS electrification and kerosene usage.

Considering costs comprehensively, including the reduction in energy costs for kerosene and batteries and the cost savings resulting from alterations in mobile phone charging patterns, the overall expenditure reduction for SHS owners averages to Naira 1,287.308 per month according to OLS synthesis.

4.2. Payback period

The primary economic effects that have been detected for payback time calculation include:

1) Reductions in expenditure on kerosene for lighting,
2) Candles,
3) batteries for radio use,
4) and mobile phone charging.

At the time of the survey, the SHS installations were around three years old and had not experienced any costs of maintenance. Considering no or very less maintenance issues in the future, the monthly savings amount to Naira 3252 for 11 W SHS users. Payback time for these users who have spent Naira 56,000 on 11 W SHS is 17.22 months or 1.43 years.

SHS household with biggest installation of 50 W solar panel, priced at around 256,000, encounter a monthly saving of Naira 4149.65.

Table 7
Effect of SHS on monthly fuel consumption

	OLS
No. of Candles	−9.969
Gas in Kg	3.019
Kerosene for cooking in liter	−0.538
Kerosene for lighting in liter	−1.92
Charcoal in Kg	0.123
Firewood in bundle	−1.03
No. of Batteries	−2.076

Table 8
Effect of SHS on monthly expenditure in Naira

	OLS
Candles	−199.384
Gas	3019.23
Kerosene for cooking	−700
Kerosene for lighting	−2501
Charcoal	24.615
Firewood	−515.384
Batteries	−415.385
Monthly cost for all energy resources	−1287.308

Payback period of these users is 61.69 months or 5.14 years. This is just above the calculations made by Wagner et al. [19] for Kenya.

4.3. Impact on carbon dioxide emissions

Based on the estimates in Table 7 and assuming the operability of SHS to be for 20 years, SHS users are on a path of avoiding the use of 119.628 candles, 6.456 liters of kerosene for cooking, and 7.932 liters of kerosene for lighting, as well as 12.36 bundles of firewood.

Each candle, burning for 10 h, emits approximately 10 grams of CO_2 per hour [26] resulting in a cumulative emission of 23.9256 kilograms over two decades. Similarly, the combustion of kerosene, with an emission factor of 2.5 kilograms of CO_2 per liter [27], would contribute to 322.8 kilograms for cooking and 396.6 kilograms for lighting. Firewood, with an emission factor of 1.8 kilograms of CO_2 per kilogram bundle [28], would lead to emissions totaling 444.96 kilograms. This corresponds to each SHS household being responsible for saving up to 59.4 kg annually and 1.188 metric ton of carbon dioxide emissions during SHS's operational period of 20 years. This saving however small is comparable to one found in research analysis by Sarker et al. [29] and Mukherjee and Ghosh [30].

5. Conclusion

Result of the analysis highlights the overall effectiveness of off-grid solar systems in mitigating energy poverty. SHS owners experience a substantial improvement in lighting usage, with a significant shift towards cleaner and more sustainable energy sources. LED lamps are used for approximately 4.125 h per day by SHS owners, which is 2.8 times more than non-SHS users and is leading to a reduction in the daily use of dirty lamps to around 76 min when compared with OLS results of non-SHS users. This shift in energy consumption patterns is reflected in the decreased reliance on traditional sources like candles, kerosene for lighting, and batteries, resulting in notable reduction in energy-related monthly expenditure among SHS owners.

Moreover, SHS ownership is associated with positive economic impacts for households. The overall energy-related monthly expenditure reduction for SHS owners, calculated by OLS, is around 1287.308 Naira less than non-SHS users. Table 8 shows the effect of SHS on monthly expenditure in Naira. This economic saving is derived from decreased spending on traditional energy sources like candles, kerosene, and batteries. While the payback period for the initial investment in SHS may seem relatively long based solely on replacement costs, the number does not fully display the superior quality of lighting and the reported positive effects on education, comfort, security, and social interaction.

In addition to economic benefits, the study indicates changes in electronic device usage patterns. SHS owners are more likely to own and use electronic devices, particularly TVs, for longer durations compared to non-owners. This suggests increased electricity consumption and stimulates local economies through heightened demand for electronic devices. The data also underscore the potential economic opportunity associated with providing mobile phone charging services within the community, although the financial gains from such services are noted as modest.

Furthermore, the impact of SHS ownership extends beyond individual households to environmental considerations. SHS ownership contributes to a reduction in carbon dioxide equivalent greenhouse gas emissions, primarily attributed to the decrease in kerosene use. The estimated annual decrease of approximately 59.4 kilograms of carbon dioxide equivalent emissions per SHS highlights the environmental benefits associated with adopting off-grid solar systems. In summary, the analysis paints a comprehensive picture of the multifaceted impacts of off-grid solar systems on reducing energy poverty and influencing local economies. The positive effects on lighting, economic savings, electronic device usage, and environmental considerations collectively position SHS as a viable and impactful solution for sustainable energy access.

Recommendations

The analytical findings offer granular insights with direct applications on the nationwide level, providing a wealth of information for academia, market participants, and policymakers alike.

Academia stands to benefit significantly from this research, as the study illuminates the multifaceted socio-economic impacts associated with SHS adoption. Notably, the work highlights a need for more in-depth exploration of the intricate relationships between SHS ownership and key socio-economic indicators, including education, health, and social interaction. Longitudinal studies can be instrumental in unraveling the long-term effects of SHS on households and communities, contributing valuable knowledge to academic discussions on sustainable energy solutions.

Moreso, future studies that include intergenerational impacts and the potential for creating positive feedback loops in terms of economic growth and human development are suggested. Moreover, comparative analyses between regions with varying levels of SHS penetration can shed light on the factors influencing adoption rates and the resulting socio-economic outcomes, informing targeted policy interventions.

For market players in the renewable energy sector, the analysis yields actionable insights that can inform strategic decisions. The economic benefits identified for SHS owners, particularly the highlighted marketing points such as superior lighting quality, extended TV-watching time, and reported positive effects on education, comfort, and security, provide a foundation for refining business strategies. The research suggests emphasizing these aspects in marketing campaigns could enhance the appeal of solar systems. Furthermore, market players might explore innovative financing options to increase accessibility, especially in regions with high energy poverty rates. This approach aligns with the data-driven understanding of consumer preferences and economic considerations.

Policymakers can leverage the study's outcomes to craft impactful sustainable energy policies at the national level. The demonstrated reduction in carbon dioxide equivalent emissions and the economic savings associated with SHS ownership present a compelling case for incentivizing and subsidizing solar system adoption. Policymakers should consider designing comprehensive programs that promote widespread access to SHS, with targeted initiatives for vulnerable and underserved communities.

Promoting the local manufacturing and distribution of SHS components can emerge as a pivotal strategy for stimulating economic growth and job creation, aligning seamlessly with international agendas for sustainable development. This approach could hold the promise of not only alleviating energy poverty but also fostering broader socio-economic benefits. By establishing local manufacturing facilities for essential SHS components such as solar panels, batteries, and charge controllers, communities can witness a surge in job opportunities, ranging from assembly line workers to skilled technicians and engineers. Collaborating with international experts facilitates technology transfer, empowering local employees with valuable knowledge and skills. Economic diversification can be achieved as the SHS industry becomes a new focal point, contributing to a more resilient and balanced economy. The development of a robust supply chain, sourcing raw materials locally, and fostering entrepreneurship in assembling and servicing SHS components all contribute to a more accessible and affordable energy landscape. Moreover, such strategy encourages community engagement, ownership, and environmental sustainability, ultimately promoting a holistic and inclusive transformation in the energy sector at the grassroots level.

Conflicts of Interest

The author declares that he has no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author contribution statement

Obinna John Anagbakwu: Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization.

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