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Willingness to pay for solar off-grid lighting in rural India

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ABSTRACT

This paper attempts to quantitatively determine the factors that affect the adoption of solar off-grid lighting products from the experience of using solar study lamps. The discrete choice experiment method is applied where the rural household in the primary survey is asked to reveal their willingness to pay for solar off-grid lighting products like Solar Pocket lamp, Solar Hurricane lamp, and Solar Home Lighting System (SHLS) in the pre-intervention and post-intervention stages. The baseline (pre-intervention) and impact (post-intervention) data helps to check whether exposure to the use of solar off-grid product technology will improve familiarity and boosts confidence, which in turn results in a higher willingness to pay for the products. The data analysis using Tobit regression reveals that the willingness to pay significantly rises in the post-intervention phase in the case of all three products. This study examines the factors influencing 'base of pyramid' households' willingness to pay for solar off-grid lighting systems in India. Using data collected from 663 households, it is identified that the money spent on kerosene lighting, electricity reliability, household type, total assets, and knowledge of the health effects of kerosene, the specification of the solar panel, the number of solar lamps, and the functioning status of the study lamp are major determinants of the willingness to pay for solar off-grid technologies.

Contribution/ Originality: This is a study based on the primary survey conducted among the users of the solar study lamps and how the success or failure affects feedback on off-grid solar lighting technologies. The respondents are energy-poor families in rural India, and the results show that technology is an experiential good. This can be categorized as a market research study on frugal energy innovations, their delivery, and after-sales services among the bottom of the pyramid population.

1. INTRODUCTION

India is committed to increasing the domestic renewable capacity to 500 gigawatts (GW) by 2030 using multiple energy sources as part of the march towards clean energy policy (IEA, 2022).The huge potential of solar energy encouraged the Indian government to launch the National Solar Mission (NSM) in 2010 to move away from unclean sources of lighting like kerosene. The goal of NSM is to innovate, identify the market, and scale up solar manufacturing capability for indigenous production and market leadership. The initial target was to build 20 GW of grid-connected solar power by 2022, and NSM revised its target in 2015 to 100 GW by 2022.

However, it never limited its scope to just grid-connected schemes, as it was also targeted to promote off-grid applications, reaching 1000 MW (megawatts) by 2017 and 2000 MW by 2022 (TERI, 2018). This is crucial, as the government aims to provide solar PV-based applications in areas where grid power is either not available or is unreliable. Off-grid applications such as solar home lighting systems, solar street lighting systems, solar power plants, solar pumps, solar lanterns, and solar study lamps are covered under the programme.

Keeping this in view, the Ministry of New Energy Resources (MNRE) has intervened with a solar off-grid lighting scheme for rural India in the name of the One Million SoUL Program (MSP), and later it was scaled up to seven million solar lamps. This model focuses on rural areas without or very little electrification with an off-grid solar study lamp for schoolchildren without addressing any other energy needs. The project aimed to provide solar-powered study lamps to one million schoolchildren between the ages of 5 and 17 in four states of India—Madhya Pradesh, Maharashtra, Odisha, and Rajasthan—in the first phase so that they could study during dark hours without depending upon the kerosene lamp or the chimney light from the kitchen. The central ministry subsidized the project, EESL (Energy Efficiency Services Limited), and other philanthropic partners who made it affordable to the consumer. The project targeted 72 geographically dispersed sub-districts, covering more than 7,900 villages (Census of India, 2011). Of the 72 sub-districts, 76 percent are designated as tribal (more than 50 percent of the population belongs to the indigenous population of Scheduled Tribes) (Census of India, 2011), and an average of 51 percent of the households depend on Kerosene as their primary source of lighting. The Indian Institute of Technology Bombay (IITB) was the primary coordinating body for identifying locations, partner NGOs, and solar lamp vendors. It was also responsible for setting the price of solar lamps and establishing service repair centres (SRCs) to provide after-sales maintenance.

This project of MNRE, which started with a target of one million and later scaled it up to seven million, is an example of frugal innovation, an indigenously developed product that caters to local demand according to the scope of the market. It tailored a unique model of LAS (Localization, Affordability and Saturation) for speedy dissemination of the product. The 'localization' goal focuses on local communities to make informed choices about technology adoption and to enhance the skill by involving them in processes like assembly, distribution, and after-sales services of the product. This will instill confidence in people towards the adoption of less-familiar technology. Affordability is key to the adoption of the technology, especially for energy-poor people. A large part of the lamp is subsidized and the beneficiary price is fixed at Rs 120 ($1.5)[1]. The saturation goal is to ensure that in each intervening block, the target group of school students has an opportunity to purchase the subsidized lamp by providing economies of scale as well as the provision of after-sales service *(threshold kept as reaching 75% of the total enrolled rural school students in the block)*. The study shows that sales, distribution, and after-sales can be related to the broad area of frugal energy technologies, where energy delivery can be made at an affordable price based on effective use of local resources and skills and renewable energy. The fact that rural India has poor access to modern energy makes India an ideal place for cost-effective energy innovations designed for consumers at the base of the pyramid. The rural bottom of the pyramid (BoP) market in India has high potential, with an approximate population of 700 million people in rural areas (Shukla & Shreya, 2011). The experience of the LAS model shows that it successfully tackled barriers from all fronts (micro, meso, and macro) to a large extent and could ensure the speedy dissemination of the study lamps. This bottom-up approach to decentralized/localized planning enables the rural poor to access power or helps them switch to cleaner sources. The objectives of this study have been to examine the factors that lead to the adoption of solar off-grid lighting products based on the experience of using study lamps provided through MSP. To check if the program is sustainable even without subsidies, this paper applies a discrete choice experiment to check the willingness-to-pay

[1] This was fixed after considering the average daily wage earned by an individual unskilled laborer employed under the Government of India's Mahatma Gandhi National Rural Employment Guarantee Act (MNREGA) scheme.

(WTP) for solar off-grid lighting products. This study used a discrete choice experiment to assess the WTP for solar off-grid lighting products in two periods: before and after the use of a solar study lamp. It is an attempt to compare the two scenarios of pre-use and post-use (separated by 11-12 months) of the product when social, economic, non-income, and energy factors remain unchanged. The quality and health factors also find space in the Tobit regression model, which estimates the willingness to pay of rural BoP households. Checking the factors driving the adoption of frugal technologies is essential in the light of the ambitious national policy initiative '24*7 Power for All' of India's central government, which aims to provide electricity to all households, industry, commercial businesses, public needs, any other electricity-consuming entities, and adequate power to agricultural farm holdings. To address the complex and heterogeneous nature of electricity production and distribution, regional policies and plans must complement national policies and attempts for energy access and sustainable energy in India. This requires frugal technology adoption, and prudential choice in technology adoption requires proper assessment of need, analysis, understanding the scope of assimilation, and provision of capacity building in the long run. Technology transfer often depends on donor preference rather than local demand. As opposed to the top-down model of centralized planning, which applies a 'one size fits all' idea irrespective of the social, cultural, and economic conditions of communities, decentralized planning assesses the needs of the target population and possible barriers and hindrances that can occur in the implementation. The subsequent sections of the paper are structured in the following manner: Section 2 offers a concise overview of the existing literature about the impact of several factors on the adoption of solar energy systems by households. Section 3 covers the topics of data, sampling, and empirical methodology. The descriptive and econometric results are reported in Section 4, and the key conclusions and policy recommendations are presented in Section 5.

2. LITERATURE REVIEW

The existing literature on the adoption of solar technologies by households shows that information policy and pecuniary incentives play a major role in adoption or willingness to pay for environmentally friendly technologies like solar power. Exposure to solar off-grid products and technology will improve familiarity with technology and boost confidence, resulting in a higher willingness to pay for the products. Studies have also shown that subsidies were also used to motivate households to incentivize the use of solar energy technologies. Etongo and Naidu (2022), in their study on household adoption of solar technology in the Seychelles, identified that cost-saving and energy security factors and environment-friendly perceptions motivated their adoption, while at the same time, the non-adoption of solar technology was due to the availability of low-cost electricity, high initial costs, existing loans, and long payback times. Grimm, Munyehirwe, Peters, and Sievert (2016) looked at how and why a very small photovoltaic (PV) kit was adopted in rural Rwanda. They found that affordability was a big reason, and they suggested direct financing or subsidies to encourage people to buy them. Grimm, Lenz, Peters, and Sievert (2020) find that households' willingness to pay for solar technologies in rural Rwanda is less than cost-covering prices. Aarakit, Ntayi, Wasswa, Adaramola, and Ssennono (2021) shed some light on the adoption of solar PV in Uganda, and it shows that flexible payment mechanisms make it more affordable for the rural population. The study concludes that solar companies should offer different payment modalities to target rural household, and demand will be ensured. Bensch, Grimm, Max, Langbein, and Peters (2016) showed that the availability of well-performing and less costly unbranded devices played a major role in the adoption of solar technologies by households. Irfan, Yadav, and Shaw (2021) investigate the peculiarities of the adoption of solar technology among Indian households and recognizes the importance of factors other than affordability, like the spirit of entrepreneurship, as well as household characteristics like family size and participation in the casual labor force. However, there is a significant difference in WTP between developed nations with reliable electricity supplies and developing countries with BOP consumers. Numerous studies provide a good explanation for the positive correlation between income and WTP for green attributes. Chowdhury and Mourshed (2016), in the context of the scope of Solar Home Systems (SHS), argue for an effective regulatory mechanism to ensure quality assurance and the protection of consumer rights, to maintain public confidence, and to ensure sustained adoption. Pepermans (2011) showed that in Belgium, the main factors influencing the WTP for renewable energy sources include income, educational level, high electricity bills, and environmental awareness. Carlsson and Martinsson (2007) showed that Swedish customers are willing to pay a higher premium to avoid power outages. It was revealed that pay plans differed between planned outages and unplanned outages. In Ghana, Taale and Kyeremeh (2016) showed that socioeconomic characteristics like monthly income, prior notice of power outages, business ownership, a separate electricity meter, household size, and education were significant predictors of household willingness to pay for reliable and quality electricity in the rural areas of Ghana. Scott (2017) stressed the importance of community participation, interaction, local capacity building, and addressing specific barriers faced by the market for off-grid solar lighting. While dealing with BOP consumers, the bottlenecks in financing the upfront costs, concerns about distribution networks, product operations like installation and maintenance, and attention to quality control must be addressed, along with the development of viable business models for off-grid renewables.

Unlike fast-moving consumer goods (FMCG) with high market penetration, consumer durables must meet several challenges before establishing themselves. When the poor could easily adopt goods like mobile phones, Coca-Cola, and detergents, jam, shampoos, etc. in small sachets, the adoption of durable goods like cook stoves or solar off-grid lighting products would differ in terms of market penetration. Sustainability and scalability of product adoption depend upon several factors, like the nature of the product, motivation, affordability, and level of community engagement. At the same time, some studies, like the one conducted by IISD & TERI (2019), looked at the savings using solar lighting compared to that of kerosene. They did a cost comparison and established that the government could save Rs 129/month ($ 1.6), Rs 41/month ($ 0.5), and Rs 37/month ($ 0.46) on each household if kerosene as a lighting source is swapped with a solar lantern, solar home system, and micro grid respectively. Studies focus on the argument that consumer's needs, ability, and willingness to pay depend upon history, cultural preferences, availability of substitutes, location, and socioeconomic background. Rural populations are usually close-knitted, and community involvement by local people serving as salespersons or distributors can promote the demonstration effect and improve 'word-of–mouth' prospects in a BOP market (Komatsu, Kaneko, Ghosh, & Morinaga, 2013). For example, in the non-electrified part of Uttar Pradesh, India, Alem and Eugenie (2018) showed that information provision and social networks played an important role in the acquisition of solar lanterns. The solar lanterns were randomly distributed to "seed' households, and the friends and relatives were offered the chance to purchase these lanterns based on the feedback received from them. The study showed that the willingness to pay for the lantern was higher due to the provision of information. Socio-demographics, income, non-income factors, energy, and quality factors do have a significant role in the sustained adoption of consumer durables like solar off-grid lamps. Multiple studies on Solar Home systems in Bangladesh reveal that household income, kerosene consumption, ownership of rechargeable batteries and the number of mobile phones, poor experience with SHS batteries, and frequency of repairs and replacements are the key determinants of adoption and user satisfaction (Komatsu, Kaneko, Shrestha, & Ghosh, 2011).

3. METHODOLOGY

The paper applies a discrete choice experiment (DCE) for deriving the willingness-to-pay estimates of various solar off-grid lighting products in two time periods. The DCE is chosen as it is a quantitative technique for evoking individual preferences over hypothetical alternative scenarios. The bunch of attributes (qualities) describe each hypothetical scenario, and the respondent will determine their preference. This method is close to the real-life decision-making process. Valuing the bunch of attributes will not be very easy, and this issue would arise for products and services not traded on the market, such as a new product under development that is not yet commercially available. Similarly, if there is no variation in the products available (or services provided), it is not possible to isolate the contribution of each product attribute to the overall utility derived from the product (Hanemann, 1994).

3.1. Conceptual Framework

The theoretical basis of the choice experiment is based on random utility theory and Lancaster's theory of consumer choices. The WTP for various solar off-grid products depends upon the utility derived from the product's attributes and the respondent households' socioeconomic characteristics. The household's utility function takes the form expressed in Equation 1:

$$U_{ij} = V\ (C_{j,} S_i) + e(C_{j,} S_i) \quad (1)$$

Equation 1 indicates that a utility U_{ij} will be associated with household 'i' for choosing a solar product 'j' (Solar pocket lamp, Solar hurricane lamp, Solar Home Lighting Systems), as expressed in Table 1 along with the market price of different solar products. Therefore, utility (U) depends on the attributes of the chosen form of off-grid lighting j (C_j) and the socioeconomic variables (S_i) of the respondent household i. The random utility framework says that the utility of choice has a deterministic part (V) and a stochastic part (e) that is not related to the deterministic part and has a set distribution. It is assumed that a rational respondent will be selecting the choice from which they derive maximum utility, given the budget constraint. The choice between the alternatives is a function of the probability that the utility is associated with the bundle of attributes of the solar product. For example, it is expected that the utility associated with SHLS is higher than that of solar hurricanes and Solar pocket lamps. As a result, SHLS is considered the most superior of the alternatives. The probability that household 'i' will choose alternative j over some alternative h within choice set R when the expected utility for household i (U_{ij}) is higher than the expected utility (U_{ih}) for all alternatives or options can be represented as Equation 2:

$$P_{i(j)} = Pr\ \{U_{ij} \geq U_{ih,}\ s.t. \forall h \epsilon Ri, and\ j \neq h\} \quad (2)$$

We assume that the relationship between utility and socioeconomic characteristics is linear in the parameters and variables and that the error terms are independent and identically distributed with a Weibull distribution (Binilkumar & Ramanathan, 2009). The probability of any particular alternative j being chosen can be expressed in a logistic distribution, as in Equation 3:

$$P_{ij} = ev_{ij}\ /\ \Sigma ev_{ih} \quad (3)$$

The general estimation model of indirect utility function is expressed in Equation 4:

$$U_{ij} = \alpha + \beta_1 C_j + \Upsilon_1 S_1 + \Upsilon_2 S_2 + \cdots \ldots \ldots \ldots \ldots . + \Upsilon_n S_n + e \quad (4)$$

β is the coefficient for the i^{th} household while choosing j^{th} product and Υ_1 to Υ_n are coefficients of various socioeconomic variables from S_1 to S_n and e is the error function of the utilities.

3.2. Description of the Data and Study Area

Primary data was collected through two rounds of primary surveys from 663 households in the intervened blocks (sub-districts) of four states of India. These households were part of the treatment group designed for the MSP, which distributed solar study lamps to school children at subsidized prices. The project's twenty blocks of four intervention states had 11,328 treatment households. Following Krejcie and Morgan (1970), a proper sample size for a population can be anything equal to 380, and we scaled up our sample size to 663 households to include as many households of varied socioeconomic backgrounds as possible. The beneficiary children and their households belong to blocks of four selected sub-districts each from the four Indian intervention states: Beohari (Madhya Pradesh), Garhi (Rajasthan), Trimbakeshwar (Maharashtra), and Jharigam (Odisha). The high dependence on Kerosene for lighting and the dominant presence of the indigenous tribal population led to the selection of these four blocks. The baseline survey was conducted in the pre-intervention period before the solar study lamps' distribution. The impact survey was conducted in the post-intervention period, almost a year after the distribution of lamps. The baseline surveys in all four states were completed from December 2017 to January 2018, and the impact surveys were conducted from November 2018 to December 2018. The two-stage surveys carried out with a gap of 11–12 months helped to make the study and results more reliable as the adoption of a technology is more related to the experience and confidence of consumers. This study tries to look at the scope of the expansion of off-grid solar technologies based on consumers' experiences. While most studies referred were based on one-stage analysis and tried to identify the barriers to the non-adoption and drivers of adoption of solar technologies, the study by Gretebeck (2017) looked at the impact assessment of solar lighting in the context of the Panasonic solar light initiative in rural areas of India with a follow-up impact study within nine months of the distribution date (Gretebeck, 2017). This study also collects information at two stages: pre- and post-intervention, which is a follow-up study to gather details on the changing perceptions of consumers towards solar off-grid lighting products.

Table 1. Attributes and market price of various solar Off-grid products along with the cost comparison with kerosene (INR (Indian Rupee).

Solar off-grid products and their attributes	**Units**	**Solar pocket lamp** 	**Solar hurricane lamp** 	**Solar home lighting system** 
Technical parameters				
Solar panel capacity	Watt	0.5-watt	2.5-watt	6 watts
Lighting capability		LED (Light emitting diode) Wattage: 0.5 Watt	LED Wattage: 1 Watt	LED Wattage: 2 Watt
Battery capability		2 lighting modes: high bright and normal bright; high bright mode: 3 hours Normal mode: 5 hours	2 lighting modes: high bright and normal bright, Super bright mode: 4 hours; bright mode: 8 hours	There are three lighting modes: bright (4 hours), medium (8 hours), and bed light (5 hours). In addition, it supports 5-pin adapters to support mobile phones.
Economic parameters				
Capital cost of solar product	INR (USD)	350 ($ 4.375)	2000 ($ 25)	5000 ($62.5)
No. of households served		1	1	1
Life cycle of product	Months	18	36	48
Levelized monthly cost per household 1	INR (USD)	19.4 per month ($0.24)	55.5 per month ($ 0.69)	104 per month ($ 1.3)
Kerosene average monthly cost per household*	INR (USD)	60 ($ 0.75)	60 ($ 0.75)	60 ($ 0.75)
Monthly cost of change per household	INR (USD)	-40.6 9 ($ 0.5)	-4.5 ($ 0.056)	44 ($ 0.55)
Average monthly govt kerosene subsidy per household**	INR (USD)	113 ($1.41)	113 ($1.41)	113 ($1.41)
Net monthly cost of kerosene to solar swap	INR (USD)	-153.6 ($ -1.92)	-117.5 ($ -1.468)	-69 ($ -0.86)

Note: * Average monthly household kerosene expenditure of our sample from PDS comes around INR 60.
** Average household cost and government subsidy is calculated by using market average of retail and public distribution system (PDS) kerosene between April and October 2018.
1 USD = 80 INR

Source: Indian Oil (2019).

The purpose-designed questionnaire in both periods was prepared to collect household information. In the first part of the baseline questionnaire, each household was asked to give general information on their background, which included questions on income, occupation, material and livelihood possessions, social group, religion, education, energy needs, sources of energy available, their reliability, health risks, and expenditures incurred on them. The second part of the questionnaire presented the choice experiment card, which comprised information on the technical features, attributes, and market price of three solar off-grid lighting products. A choice card is used as an instrument to elicit preferences so that one can evaluate the willingness to pay for different attributes related to what the product offers. The image and description of features in the choice experiment card help the respondent connect with the product's benefits. It also plants the idea of getting access to light without a grid connection, as most of the respondents have no experience with solar off-grid products.

In the second round of the survey (post-intervention), the households were approached to get feedback on the use and quality of the solar lamp, their working condition, and the provision of repair and maintenance centres. The same choice card with three solar off-grid lighting products is given to assess the WTP for the same products for the second time to investigate whether exposure to a technology or product can significantly affect the WTP for the products. Technology is an experience, and this choice experiment investigates whether using solar study lamps (SoUL) has made the consumer more confident about the technology. After-sales services and a one-year lamp warranty have an essential role in addressing quality and performance issues. The impact study was prepared to procure feedback on the use of the SoUL study lamp and the changing attitude of consumers towards relatively new technology, assuming no dramatic change has occurred within a year in the household or village that has altered the socioeconomic characteristics of the households. Table 1 shows the choice card that was presented to the respondents in the two surveys. Along with this, a cost comparison of three solar off-grid lighting products with kerosene is also given.

Table 2. Socioeconomic details of the households.

Head of the household	%	N	Type of card	%	N
Male headed household	99	657	Below poverty line (BPL)	73	484
Female headed household	1	6	Antyoday	20.51	136
Annual income ($) per household	%	N	Above poverty line (APL)	3.77	25
<=$780	93.3	619	No card	2.26	15
>$780	6.63	44	Others **	0.45	3
Total number of household articles/Gadgets	%	N	Primary source of income	%	N
<=10	90.64	601	Agriculture	43.29	287
>10	9.35	62	Agricultural labour	14.18	94
Total number of cattle	%	N	Non-agricultural labour	2.26	15
<4	67.7	448	Diary	9.50	63
>4	32.4	215	Service	20.21	134
Kerosene reliability of household	%	N	Agriculture +agricultural labour	2.41	16
Reliable	84.01	557	Agriculture + non-agriculture labour	2.26	15
Not reliable	15.98	106	Skill based occupation	0.15	1
Electricity reliability of household	%	N	MGNREGS	1.36	9
Partially reliable	44.6	126	Remittances	0.15	1
Not reliable	55.35	156	Others	4.22	28
Household type	%	N	Social group	%	N
Kuttcha	39.5	262	Scheduled tribe (ST)	70.44	467
Semi-pucca	54.4	361	Scheduled caste (SC)	7.09	47
Pucca	6.03	40	Other backward caste (OBC)	13.12	87
Money spent on kerosene lighting per year/Household ($)	%	N	Open (General)	9.35	62
<=$10	49.3	327	Households State-wise	%	N
>$10	50.6	336	Beohari (MP)	20.51	136
No: of houses with electricity connection and meter	42.5	282	Garhi (RJ)	9.50	63
Electricity bill per year /Household ($)	%	N	Trimbak (MH)	47.51	315
<=$25	69.0	195	Jharigham (OD)	22.47	149
>$25	30.9	87			

Note: ** means significant at 5% level.

Table 2 summarizes the socioeconomic characteristics of the sample households from four selected districts of four states: 20.5% from Beohari (Madhya Pradesh), 9.5% from Garhi (Rajasthan), 47.5% from Trimbak (Maharashtra), and 22.5% from Jharigham (Odisha). The sampled data has around 99% male-headed households, 93.3% of households with an annual income less than \$780, 73% belonging to BPL (below the poverty line), and 20.51% 'Antyoday.' ('Poorest among the poor') card-holders. The occupation profile of the sample shows that 43.29% of households depend upon agriculture as the primary source of income, 20.2% depend on the service sector, and 14% work as agricultural labor for a living. Most households have very minimal household items and gadgets at home, and around 54% of them live in semi-pucca (semi-well-built) houses, while 39.5% live in *kutcha* (mud-thatched) houses. The large representation of agriculture in the occupation profile and 9.5%, depending on the diary, should relate to the 68% of households owning cattle.

From Table 2, it is evident that the most dependable fuel in Indian villages is Kerosene. About 84% of households consider Kerosene reliable, whereas 55.3% think grid electricity in the village is non-reliable. The coexistence of kerosene and grid electricity, one with high reliability and another with zero or partial reliability, shows the dualism of India's rural energy setup.

3.3. Empirical Model

Most of the studies on adoption of solar technologies used econometric models like logit and probit, which suited the research design. In this work, censored regression is used for analysis, and the dependent variable stated, WTP, is censored with a lower bound of zero. One main characteristic of the data is that there are observations where the dependent variable (WTP) is zero. The respondent households' affordability quotient and lack of experience and faith in a new product or technology can result in a low or zero valuation. Therefore, this model does not hold the linearity assumption in Ordinary Least Square. The Tobit model is most suitable. We observed that households' responses to their maximum willingness to pay comprised zero and positive values. In Tobit estimation, the latent dependent variable equals the observable dependent variable when the latent variable is not negative (Wiencke, 2013). The number of people who have zero WTP has reduced in the post-intervention period. Specifically, around 64% and 36% of households reported zero willingness to pay in the pre-intervention period. This makes the Tobit model the most suitable for empirical analysis. The model is expressed as:

$$WTP_i *= \beta x_i + e_i > 0 \qquad (5)$$

$$WTP_i = max\ (0, WTP_i *) \qquad (6)$$

Where WTP_i is the latent variable, x_i is a vector of independent variables, β is a vector of parameters to be estimated, and e_i are residuals that are assumed to be independently and normally distributed with a mean of zero and an expected variance of σ^2. The WTP is unobserved below the censoring limit, which is zero and can be observed only when it takes a positive value. Unlike linear models, the marginal effect for a given explanatory variable in the Tobit model estimations is non-linear and thus not equal to the β_i (Taale & Kyeremeh, 2016). Equations 7 and 8 have been formulated for the empirical analysis.

$$WTPij = (\alpha + \beta_1 AI + +\beta_2 TOTASSETS + \beta_3 KERORE + \beta_4 ELECRE + \beta_5 HHTYPE + \beta_6 MSKYEAR + \beta_7 EBILLYEAR + \beta_8 HLDSHEDDING + \beta_9 KEROHEALTH + \beta_{10} SOLPANEL + e_i \qquad (7)$$

Equation 7 estimates the WTP (willingness to pay) of i^{th} household for j^{th} solar off-grid product in the *pre-intervention* (*baseline*) period as a function of the explanatory variables in the model.

$$WTPij = (\alpha + \beta_1 AI + +\beta_2 TOTASSETS + \beta_3 KERORE + \beta_4 ELECRE + \beta_5 HHTYPE + \beta_6 MSKYEAR + \beta_7 EBILLYEAR + \beta_8 HLDSHEDDING + \beta_9 KEROHEALTH + \beta_{10} SOLPANEL + \beta_{11} NUMLAMP + \beta_{12} LAMPFUNCT + e_i \qquad (8)$$

Equation 8 estimates the WTP (willingness to pay) of i^{th} household for j^{th} solar off-grid product in the *post-intervention* (*impact*) period as a function of the independent variables in the model. The dependent variable WTP in both cases is the amount households are willing to pay for the solar off-grid product after knowing about its features and perceived utility from consumption.

$$WTP_{ij}\ (\delta V/\delta x)/(\delta V/\ \delta p) = -\ \beta_{\text{attribute level of the product}}/\beta_{\text{price}} \quad (9)$$

Equation 9 represents the marginal rate of substitution (MRS) between price and the value of products. This indicates the value of solar off-grid products as perceived by households that participated in the household survey. WTP is the implicit price (expressed in monetary terms), or the worth of the product attribute, and the socioeconomic characteristics of the respondent.

Table 3. Definition of explanatory variables in the model.

Variable	Expected sign.	Explanation
Income/Affordability factors		
AI (Annual income of the household)	+ve	Higher the annual income of the household, the higher the WTP (Aarakit et al., 2021; IFC & World Bank, 2010; Komatsu et al., 2011; Wiencke, 2013).
TOTASSETS (Aggregate of household appliances)	+ve	Total assets are an indicator of the wealth and affordability of a household.
HHTYPE (Household type) 0- Kuchha house, 1- Semi Pucca, 2- Pucca house	+ve/-ve	House type points at the affordability factor of the household (Taale & Kyeremeh, 2016).
Energy factors		
KERORE (Kerosene reliability) 0- not reliable, 1-reliable/Partially reliable	-ve	This variable is according to the perceptions of people about the supply of kerosene. WTP for alternate sources will rise if the reliability of kerosene is low.
ELECRE (Electricity reliability) 0-not reliable, 1- Reliable/Partially reliable	+ve/ve	This variable is according to households' perceptions of the reliability of grid electricity, whether they have it or not. WTP for alternate sources will rise when there is no electricity or the reliability of electricity is low.
MSKYEAR (Money spent on kerosene lighting per year)	+ve	The higher the expenditure on kerosene, the higher the WTP (IFC & World Bank, 2010; Komatsu et al., 2013; Rao, 2012).
EBILLYEAR (Electricity expenses paid for one year)	+ve/-ve	Higher the expenditure on electricity, higher should be the WTP for alternate sources, but this also helps to see if households with grid-based electricity have demand for solar off-grid products.
HLDSHEDDING (Average hours of load shedding per day)	+ve	More hours of load shedding show unreliability of electricity, which can become a factor in higher demand for renewable energy products (Carlsson & Martinsson, 2007; Taale & Kyeremeh, 2016).
Quality factors		
LAMPFUNCT (SoUL lamp working or no working) 0- working, 1-not working	+ve	Functioning lamps build consumers' confidence in the technology, and WTP rises (Chen, Zhu, Lemes, Moorthi, & Strickland, 2014; Komatsu et al., 2013).
SOLPANEL (Pocketlamp-0.5, Hurricane lamp-2.5, Solar home lighting system-6 (in Watt)	+ve	This is the only attribute variable (Discrete) taken in the model. It denotes the specification of the panel (in Watts) of each lighting device. A higher specification is expected to fetch a higher WTP.
Other factors		
KEROHEALTH (Knowledge on health effects of Kerosene)	+ve	Knowledge of the harmful effects of kerosene should encourage people to pay more for clean lighting (ATSDR, 1995; Jacobson, Lam, Bond, & Hultman, 2013; Lam et al., 2012; Pokhrel et al., 2010; Rao, 2012).
NUMLAMP (Number of SoUL lamps at the house)	+ve	The greater number of lamps purchased indicates a desire for a clean source of energy.

Table 3 explains the explanatory variables included in Equations 7 and 8, along with their expected signs. The independent variables are categorized as income factors, which indicate the affordability of the household; energy factors, which indicate the reliability of various lighting sources and the expenses of each source; quality factors, which point to the functioning of the lamp; and technical features of the lighting product.

The variable AI represents the annual income of the household, and the variable is important to assess whether solar off-grid lighting products are a normal good. The literature shows that income is positively related to WTP. Similarly, it is expected that households with more assets will have positive WTP for new gadgets like solar off-grid lights. Kerosene reliability and Electricity reliability and their direction of relationship also must be checked to reach conclusions on the level of dependency of the household on both. The variables like MSKYEAR, and EBILLYEAR are expected to have a positive relationship with willingness to pay for off-grid solar lighting products, as using alternate sources can reduce the kerosene and electricity bills. HLDSHEDDING, KEROHEALTH, NUMPLAMP, LAMPFUNCT, and SOLPANEL are also expected to positively correlate with the dependent variable. Six hundred and sixty-three households were part of the baseline and impact surveys, and we pooled the WTP for three lighting devices to get 1989 observations in both baseline and impact models. The descriptive statistics of explanatory variables in the models given in Table 4 explain that the variables annual Income (AI) and electricity bill (EBILL) show a high standard deviation. The mean AI is INR 44,800 ($560), meaning households have a daily average income of less than $1.5, and thus our sample is representative of the poorest and most vulnerable income sections of Indian society. Huge differences in annual income and a high standard deviation in electricity bills point to the fact of highly uneven income distribution and a highly unequal energy use pattern.

Table 4. Definition and descriptive statistics of variables used in the model.

Variable	Mean	Std. dev.	Min.	Max.
AI	Rs 44,800 ($560)	13136.3	34.4	1562
Totassets	4.21	64.408	0	38
Hhtype	1.665	0.586	0	2
Kerore	0.840	0.366	0	1
Elecre	0.447	0.497	0	1
Mskyear	Rs 727 ($ 9.09)	330.42	0	33.75
Ebillyear	Rs 1934 ($ 24.18)	3065.09	0	375
Hldshedding	2.207	2.09	0	5
Kerohealth	1.796	0.403	0	1
Numlamp	1.041	0.656	0	4
Lampfunct	1.66	0.474	0	1
Solpanel	3	2.27	0.5	6

4. RESULTS AND DISCUSSIONS

The focus of the study is to examine households' willingness to pay for solar off-grid lamps. The TOBIT model estimates in Table 5 and Table 6 show the explanatory variables that are influential in deciding the WTP for Solar Off-grid products in the pre-intervention and post-intervention periods, respectively. Along with marginal estimates, the variance inflation factor (VIF) is checked to rule out any evidence of multicollinearity. The mean VIF values of both pre-intervention and post-intervention indicate the absence of multicollinearity.

The factors that influence the WTP for the pocket lamps in the pre-intervention period are total assets, electricity reliability, money spent on kerosene lighting per year, knowledge of the health effects of Kerosene, and the specification of the solar panel of the product. TOTASSETS, which is an income factor that indicates households have a positive correlation with WTP.

This means households that have more gadgets tend to pay more. ELECRE shows that households with reliable grid electricity had a lower incentive to spend on alternative lighting sources. Households in 'pucca' and 'semi-pucca'(well-built) houses have a higher WTP than those in *'kutcha'* houses. However, money spent on Kerosene (MSKYEAR) shows a negative correlation with WTP, and as the money spent increases by 1%, the WTP decreases by 0.84%. KEROHEALTH has a positive relationship with the dependent variable, meaning households with proper knowledge of the health hazards of kerosene show higher WTP for solar off-grid products. The model has two more variables in the post-intervention period.

The significant predictors are MSKYEAR, house type (HHTYPE), KEROHEALTH, hours of load shedding (HLDSHEDDING), number of SoUL lamps in the house (NUMPLAMP), and working condition of the SoUL lamp (LAMPFUNCT). MSKYEAR, like in the pre-intervention period, is negatively correlated with the dependent variable, and the households living in semi-pucca and pucca households tend to pay more for the pocket lamp. Annual Income (AI) is positively correlated with the dependent variable, meaning that the solar lighting devices under consideration are normal goods. HLDSHEDDING, KEROHEALTH have a positive statistical relationship with the dependent variable.

The number of solar study lamps the household owns depends on the number of school-going children. The households with more lamps (NUMPLAMP) are willing to pay more for off-grid solar lighting products. The working status of the solar study lamp had a very significant effect in deciding the WTP, which denotes that households with at least one solar study lamp in working condition have a higher WTP than those with non-functional lamps. SOLPANEL is the attribute variable that explains the specification of the solar panels of the three solar off-grid lighting devices.

Solar hurricane and pocket lamps are the next best in terms of specification after Solar Home Lighting System (SHLS). The solar home lighting system (SHLS) comes with four lights to meet higher-order needs like lighting mobile charging points and is comparatively more expensive than the other two products. Theoretically, more attributes other than SOLPANEL can be considered in the model, but this will lead to high multi-collinearity, affecting the Tobit model's results.

Contrary to many previous studies, expenditure on Kerosene for lighting per Year (MSKYEAR) shows a negative correlation with the dependent variable. This result asks whether solar off-grid lighting devices can replace traditional kerosene lamps. In the pre- and post-intervention periods, the relation of MSKYEAR to the dependent variable in statistical terms has remained the same. The share of Kerosene is very high in the energy expenditure of the rural poor and is used for cooking and lighting.

The sample chosen for this study belongs to the base of the pyramid income group with an average income of less than $2/day, and those who spend more on kerosene think that investing in solar off-grid lights is not as dependable as Kerosene.

Though the reliability of kerosene (KERORE) and WTP is positively related, 85% of our sample considers them to be reliable fuels for lighting. From 2021 on, the Indian government stopped subsidizing kerosene. Until kerosene in India is provided through rations or fair-price shops and there are restrictive quotas for the same, if their needs exceed the quota, they will purchase it from the open market. It is essential to understand the dominant use of the fuel and its role in the lives of those who use it. There can be a dilemma between need and latent need. Historical purchase decisions and conventional wisdom, along with skepticism towards new technology, can affect the judgment of rural BoP consumers, which fails them to recognize their latent needs and leads to the continued adoption of traditional sources (Shukla & Shreya, 2011).

Two additional variables in the post-intervention model are the number of SoUL study lamps owned by the household (NUMPLAMP) and the functional status of the SoUL lamp (LAMPFUNCT) owned by households. These variables help to investigate confidence in technology adoption.

Both of these variables are significant in the case of all three products. The WTP increased with the number of lamps owned by the household. The condition of the lamp influenced the WTP for the three solar products- Pocket lamp, Hurricane lamp, and Home Lighting System- fell if the lamp stopped working between the study period.

Table 5. TOBIT estimates pre-intervention period.

Independent variables	Coefficient *(t-statistics in bracket)*	Standard error	VIF	Marginal effect
AI	0.002 (0.94)	0.002	1.04	0.001
Totassets	15.923**(2.49)	6.405	1.43	5.427
Kerore	139.215 (1.93)	72.284	1.09	44.844
Elecre	-164.165*** (2.60)	63.043	1.64	-55.405
Hhtype	210.78*** (4.26)	49.501	1.29	71.837
Mskyear	-0.846*** (8.52)	0.099	1.57	-0.288
Ebillyear	-0.003 (-0.32)	0.01	1.09	-0.001
Hldshedding	10.518 (0.84)	12.563	1.14	3.585
Kerohealth	246.369*** (4.09)	60.177	1.03	83.967
Solpanel	104.486*** (9.50)	11.001	1.00	35.611
Constant	-166.339 (-0.89)	187.107	Mean 1.23	
Log likelihood	-6484.9			
LR chi² (10)	274.72			
Pseudo R²	0.0207			
Left censored observation <=0	1280			
Observation	1989			

Note: *** means significant at 1% level, ** means significant at 5% level.

Table 6. TOBIT estimates post intervention period.

Independent variables	Coefficient *(t-statistics in bracket)*	Standard error	VIF	Marginal effect
AI	0.001 (0.28)	0.001	1.07	0.0002
Totassets	19.17*** (4.39)	4.371	1.48	12.082
Kerore	20.58 (0.44)	47.054	1.11	12.894
Elecre	-87.69** (-2.11)	41.658	1.65	-55.033
Hhtype	132.65*** (4.06)	32.637	1.29	83.604
Mskyear	-0.651*** (-10.16)	0.064	1.62	-0.4105
Ebillyear	0.001 (0.13)	0.006	1.09	0.0004
Hldshedding	23.29*** (2.80)	8.316	1.16	14.677
Kerohealth	146.584*** (3.42)	42.823	1.05	92.39
Numplamp	227.481*** (7.02)	32.408	1.07	143.37
Lampfunct	283.9*** (7.88)	36.0174	1.13	178.93
Solpanel	146.52*** (20.49)	7.149	1.00	92.34
Constant	-258.40 (-1.74)	148.35	Mean 1.22	
Log likelihood	-10479.997			
LR chi² (12)	736.7			
Pseudo R²	0.034			
Left censored observation <=0	734			
Observation	1989			

Note: *** means significant at 1% level, ** means significant at 5% level.

Around 65% of households complained about the non-functioning of the lamps and the high failure rates of the lamps, and this was identified as the result of a lack of awareness about the maintenance of the lamps, like the cleaning of the panels and the handling of the lamps. About 89% of households with non-functioning lamps did not utilize the services of solar repair centres, which offer free maintenance and services for the lamps. Wherever the issues, like lack of knowledge about the location of solar repair centres, were addressed, the confidence levels of users in the technology improved. Carelessness in maintaining the solar panels and rough lamp handling increased the number of complaints about the lamp. Considering this, awareness of the maintenance of lamps and knowledge of the location and services of repair centres can help in the sustained adoption of off-grid solar lighting products and can lead to the popularization of off-grid technology.

Table 7 shows the mean WTP of households for solar pocket lamps, solar hurricane lamps, and Solar Home Lighting System (SHLS) in the pre-intervention and post-intervention periods. The number of households that preferred to pay for these products increased after using SoUL lamps, proving that exposure to technology increases familiarity and results in a higher willingness to pay. This study shows that technology as an experiential good can lead to continued adoption if it can win consumer confidence. Income, energy, quality, and other factors can influence the WTP, and each one must be addressed with deserving priority. The results of the study align with several previous studies, like that of Gretebeck (2017), which identified that after the use of solar lighting, the perceived benefits of solar lighting in rural areas have improved significantly. Grimm et al. (2016), Grimm et al. (2020), and Aarakit et al. (2021) point out the need for incentivizing customers to take up solar lighting, especially in low-income areas, and by resorting to different customer-friendly payment modes. This study also reaffirms the importance of the subsidy given to SouL Lamp and how it helped in the subsequent rise in demand for solar lighting. Bensch et al. (2016) pointed out that inexpensive and well-performing devices can aid in the market expansion of off-grid lights, and this study also reveals that customers with functioning lamps have shown more confidence in the technology and a higher willingness to pay.

Table 7. Mean WTP of households for various solar lighting products.

Solar off-grid products	Households in Pre-intervention whose WTP>0	Households in Post-intervention whose WTP>0	Mean WTP of households with WTP>0 in Pre intervention period (in INR)	Mean WTP of households with WTP>0 in post-intervention period (in INR)
Solar pocket lamp	182	420	Rs 112($ 1.4)	Rs 155 ($ 1.9)
Solar Hurricane lamp	315	414	Rs 607 ($ 7.5)	Rs 780 ($ 9.75)
Solar home lighting system	212	421	Rs 1525 ($ 19)	Rs 1555($ 19.43)

5. CONCLUSION

The post-use rise in WTP indicates a strong value proposition for Solar Off-grid lighting products and shows the need to spread awareness among consumers about the benefits and maintenance of lamps. If the percentage of failures in technology comes down, the level of confidence will gradually grow, as technology is an experiential good. The stoppage of the kerosene subsidy by the government can further influence the preferences of the 'price-sensitive' base of the pyramid population. The twin goals of projecting off-grid solar lights as an alternative option and familiarizing the customer base with the properties and peculiarities of the product should go hand in hand. Although solar off-grid lights present a 'win-win' opportunity, the real challenge lies in establishing a niche consumer base in the BoP segment. The nurturing of the consumer base is very important for niche markets. The knowledge of the harmful effects of kerosene induces households to switch to clean sources, and the absence of such knowledge would discourage investment in solar off-grid technologies. Innovative energy delivery models through awareness campaigns on the health, monetary, and environmental benefits and the provision of reliable, pro-active after-sale services can ensure the sustained adoption of off-grid solar technology.

The rural BoP population is a mixed group with varied and uncertain income and expenditure levels. They face some commonalities, like financial constraints, domestic hardships, and a lack of capability to make an informed decision on the consumption of goods and services. The earnings will mainly go towards fulfilling survival needs and health investments to reproduce their labor. Unlike durable goods like solar lighting and cook stoves, there has been a high market penetration of non-durable goods among BoP households. Frugal energy innovations compatible with rural BoP households with customized business models and practical distribution strategies are essential in addressing the energy divide in India. The scope of off-grid solar technology is the fastest, and there are strong indications that it has gained social acceptance among the targeted groups. Several government policies in the energy sector, like kerosene subsidies and taxes on renewable energy, have high implications for the potential market for solar off-grid lighting.

The paper mostly limits itself to the case of subsidized SoUL lamp, and there is difficulty generalizing findings from this case to other settings. The market for solar lighting has a lot of potential, so more focused consumer surveys using a combination of quantitative and qualitative techniques should investigate its scope. Promotion of a conducive environment for the expansion of the market for renewable technology includes demonstration programs, right-pricing of energy sources, provision of soft loans for entrepreneurs and customers through banks, and self-help groups to reach the bottom of the pyramid.

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