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Transforming Energy Access: The Role of Micro Solar Dome in Providing Clean Energy Lighting in Rural India

R. Karthik*†, Ramya Ranjan Behera, Uday Shankar***, Priyadarshi Patnaik**** and Rudra Prakash Pradhan*******

*Advanced Technology Development Centre, Indian Institute of Technology, Kharagpur-721302, India
**Rekhi Centre of Excellence for the Science of Happiness, Indian Institute of Technology, Kharagpur-721302, India
***Rajiv Gandhi School of Intellectual Property Law, Indian Institute of Technology, Kharagpur-721302 India
****Department of Humanities and Social Sciences, Indian Institute of Technology, Kharagpur-721302, India
*****Vinod Gupta School of Management, Indian Institute of Technology, Kharagpur-721302, India
†Corresponding author: R. Karthik; karthikeee34@gmail.com

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ABSTRACT

Access to affordable and reliable energy sources can substantially enhance the lives of marginalized communities in rural areas. Unfortunately, numerous households in these communities rely upon unclean sources of energy such as kerosene to light the house even during daylight. To address this issue, solar off-grid technology - Micro Solar Dome (MSD) was implemented in various states across India, specifically benefiting the scheduled caste and scheduled tribe communities. The study, across the eight selected states, highlights the advantages of adopting off-grid technologies and their roles in promoting awareness of renewable energy solutions. The survey used purposive sampling to collect community members' perceptions of the product's benefits and their awareness of renewable technologies. The results indicated that the utilization of the product not only enhanced illumination levels within households but also contributed to improved safety, increased study hours for children, and facilitated economic activities during the evening hours. Furthermore, the study revealed that education plays a crucial role in adopting solar energy. However, interventions such as awareness programs and hands-on experiences with the products can also greatly enhance awareness and promote adoption in rural areas. Overall, the study provided compelling evidence of the significant and positive impact that small-scale initiatives like the MSD can have on the lives of marginalized communities. It also emphasized the potential of such solutions to empower these communities and improve their overall well-being.

INTRODUCTION

Access to reliable and affordable electricity is essential for improving the quality of life, especially for rural households in India. However, approximately 13.8 million people in rural areas do not have access to grid electricity (World Bank 2021), leaving them reliant on kerosene lamps for lighting, which has significant health and environmental consequences (Pokhrel Amod et al. 2010). The emission from the kerosene lamps usually include black carbon and CO2, which contributes to global warming. Kerosene lamps emitted about 270,000 tonnes of black carbon, with India accounting for 12% of the emissions (Jacobson et al. 2013). The potential risk of using kerosene-based lights leads to diseases like tuberculosis, a significant health issue in developing countries. Burning candles increased the lead concentration above the ambient standards (Pokhrel Amod et al. 2010). Using kerosene lamps made women and children more prone to household-based injuries (Sharma et al. 2019).

The Government of India has implemented various vital initiatives to ensure that all areas have access to electricity. One such program, the Deen Dayal Upadhyaya Gram Jyoti Yojana (DDUGJY), designed to provide continuous electricity supply to rural households, agricultural consumers, and industries. This scheme also focuses on improving and upgrading the rural electricity infrastructure. Another significant program is the Pradhan Mantri Sahaj Bijli Har Ghar Yojana (Saubhagya), launched in 2017 to provide free electricity connections to eligible households in rural and urban areas (Malhotra 2022).

According to the International Energy Agency, the country has made the most considerable electrification effort in history, with over 99% of households having access to electricity as of 2019. Despite these initiatives, frequent power interruptions and poor power quality from the distribution side remain significant challenges (Chamania et al. 2015, Sharma et al. 2019). Additionally, electricity affordability for people in rural areas, particularly marginalized communities, is another critical factor that needs to be considered (Pelz et al. 2021).

In recent years, off-grid solar solutions have emerged as a promising alternative to traditional grid-based electricity, offering clean and reliable electricity that can improve the well-being of households and communities (Akter & Bagchi 2021). Solar technologies such as on-grid solar, solar thermal systems, and off-grid solar systems, including solar home systems, solar lighting systems, mini-grids, and solar lanterns, have the potential to provide sustainable and affordable energy access for rural areas (Mahapatra & Dasappa 2012, Sandwell et al. 2016). Solar lighting systems (SLS) and solar lanterns have garnered attention as promising affordable lighting sources for basic household needs in remote regions (Abdullah-Al-Mahbub et al. 2022). Solar lanterns are particularly suitable for rural areas to ensure basic energy access, as they are a cost-effective, easy-to-use, and sustainable solution. They provide a clean, renewable, and affordable alternative to traditional lighting methods, eliminating dependence on harmful kerosene lamps and contributing to reducing indoor air pollution, benefiting both human health and the environment (Sandwell et al. 2016). The impact of SLS and lanterns must be considered. They provide clean, reliable, and affordable electricity to marginalized communities, improving the quality of life and promoting sustainable development. The United Nations, via its Sustainable Energy for All (SE4ALL) initiative and Sustainable Development Goal 7 (SDG 7), encourages the use of decentralized solar solutions to fulfill the universal energy access target for 2030 sustainably (Banerjee et al. 2013).

This research examined the impact of pico-level solar lighting systems on the quality of life of marginalized rural households. It aimed to explore how improved illumination affects on the quality of life within these communities. Additionally, the research investigated how introducing such technologies can raise awareness of renewable energy, regardless of education level. The findings of this research were expected to provide valuable insights into the potential benefits of pico-level solar lighting systems and help promote the adoption and sustainability of these technologies in marginalized rural households.

BACKGROUND OF THE STUDY

Solar lanterns have become an increasingly popular solution for lighting in rural communities worldwide. While they have been in use for over a decade, their widespread adoption has accelerated in recent years due to the declining cost of solar technology (Kumar 2015). Governments, NGOs, and private companies have also launched initiatives to promote solar technologies in rural communities. These efforts have helped raise awareness about the benefits of solar energy and make these technologies more accessible to people in remote areas (Wong 2012). Promoting solar technologies in rural areas is essential for providing lighting and has implications for the quality of life in these communities (Rehman et al. 2010). As such, the Quality-of-Life (QoL) concept has received extensive attention in recent decades. The study on quality of life aimed to explore the relationship between various dimensions of well-being, such as health, education, economic insecurity, personal activities, political voice and governance, social connection, environmental conditions, personal insecurity, and energy usage (Seabra et al. 2022).

Solar lanterns are a promising solution to address the issues faced by rural households, particularly in terms of lighting and education. Several studies have shown that using solar lanterns can improve rural households' quality of life while reducing their expenditure on kerosene and candles, as observed in East Timor, Africa (Bond et al. 2010, Kudo et al. 2019). However, a study in Uganda did not show any favorable impact on children's schooling despite using solar lamps for their basic needs (Furukawa 2014).

Nonetheless, the solar light program in Bangladesh found that while there was no effect on academic performance, lighting helped students free from eye irritation, thus improving children's health and ensuring safety from burns (Chamania et al. 2015, Khandker et al. 2014, Kudo et al. 2019). In India, where kerosene lamps were prevalent due to the unreliability of the electricity supply, portable solar lights have been introduced to rural households under the Million Solar Urja Lamp program, increasing study hours for school-going children (Sharma et al. 2019). Therefore, solar lanterns can play a significant role in improving the lives of rural communities, particularly in terms of education and health.

Inadequate lighting is a problem that plagues low-lit areas and severely threatens the safety and well-being of vulnerable groups, especially women. Adequate lighting enhances women's security, mobility, and empowerment (Bose et al. 2021). A recent study on energy initiatives in refugee camps found that while there was no direct link between energy and women's safety, improved lighting could help prevent attacks and improve overall safety (Thorgren & Ghasemi Niavarani 2021). The benefits of solar lanterns were evident in a project in Gujarat's Dahod district, which has significantly aided rural homemakers in their daily activities and visits to agricultural fields (Agoramoorthy & Hsu 2009). Additionally, a randomized controlled trial in the Barabanki district of Uttar Pradesh demonstrated that solar-powered lighting could substantially improve women's safety (Aklin et al. 2017). A study conducted in Rwanda found it challenging to quantify the benefits of solar lanterns, yet they enhance domestic productivity and flexibility, leading to more efficient evening activities and improved study conditions, thereby improving household living standards (Grimm et al. 2017).

Finally, Increased awareness about the benefits of solar energy is crucial in promoting its adoption in rural areas (Urmee & Md 2016). Previous studies on solar adoption have found that education strongly affects adoption. For example, a study in Uganda found that non-adopters were more likely to have no formal education than adopters. At the same time, there was no statistically significant difference between non-adopters and adopters with primary education attainment (Aarakit et al. 2021).

In a study of India's solar lantern program, researchers analyzed the education level of both early and late adopters and found that early adopters generally had higher education (Velayudhan 2003). While education did not significantly influence the adopter categories, it suggested that education plays a role in the early adoption of solar lanterns. Further exploration and understanding of the perceptions of solar energy among marginalized communities are essential to promote sustainable and inclusive development.

CONCEPTUAL FRAMEWORK

The conceptual framework of this study, shown in Fig. 1, addresses two primary challenges prevalent in rural households of SC /ST communities: reduced illumination levels and a limited understanding of solar energy. The MSD installation represents the introduction of solar lighting solutions in these communities. This intervention is anticipated to bring about improvements in Illumination Enhancement within households' awareness of solar energy by imparting comprehensive knowledge about solar energy. The outcomes of this framework focus on Improved Quality of Life and Enhanced Solar Adoption.

MATERIALS AND METHODS

India has made numerous efforts to improve the growth of technological innovation to improve energy access and reduce pollution to achieve climate targets. Under Mission Innovation, a global initiative supported by DST, Micro Solar Dome (MSD) to promote clean energy technologies in rural areas (IEA 2020)—in order to increase both awareness and encourage adaptation of solar energy among marginalized rural communities. The project was implemented across 13 states—Assam, Manipur, Tripura, Himachal Pradesh, Jharkhand, Chhattisgarh, Bihar, Rajasthan, Kerala, Odisha, West Bengal, Madhya Pradesh and Nagaland. This project aimed at installing around 44,000 units, specifically focusing on benefiting the Scheduled Castes (SC) and Scheduled Tribes (ST) communities residing in rural areas. The states and villages selected for implementation were identified based on having the highest Scheduled Castes (SC) and Scheduled Tribes (ST) populations, according to the 2011 Census data. Local NGOs assisted in conducting awareness programs on renewable energy in these villages. These programs aimed to educate residents about the benefits and practicalities of the technology. Following these programs, the Micro Solar Domes were installed for individuals who

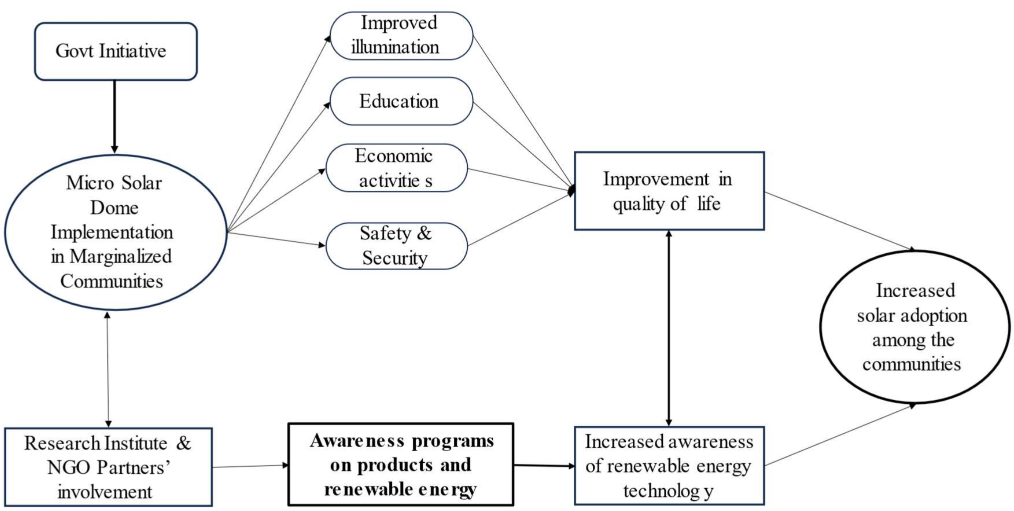

Fig. 1: Conceptual framework of the study.

Fig. 2: Micro Solar Dome.

showed interest and were willing to contribute financially to their installation.

Design of Micro Solar Dome

Fig. 2 shows the Micro solar dome, an innovative and low-cost hybrid product developed by NBIRT, Kolkata, and implemented by IIT Kharagpur.

MSD, a solar lighting system shown in Fig. 3, uses solar panels to convert sunlight into electrical energy through the photovoltaic effect. The electrical energy is then stored as chemical energy in a lithium-ion battery of 4.4 Ah (Ampere hour) with the help of a DC circuit that includes a microcontroller and a battery management system. The battery management system protects the battery from overcharging and deep discharging. When the switch is operated, it activates a LED in the lower Dome that converts the stored electrical energy into light. Additionally, the device includes a USB port that enables users to charge their mobile phones using the stored electrical energy, and it provides a 2-meter-long charging cable for user convenience.

The system featuring the PCB circuit incorporates an LED indicator that displays the battery's charging status from the solar panels. A provided DC connector allows users to power the LED light from the grid supply directly in cases of insufficient battery power. The battery provides backup lighting for approximately 5-6 h per day. To enhance the

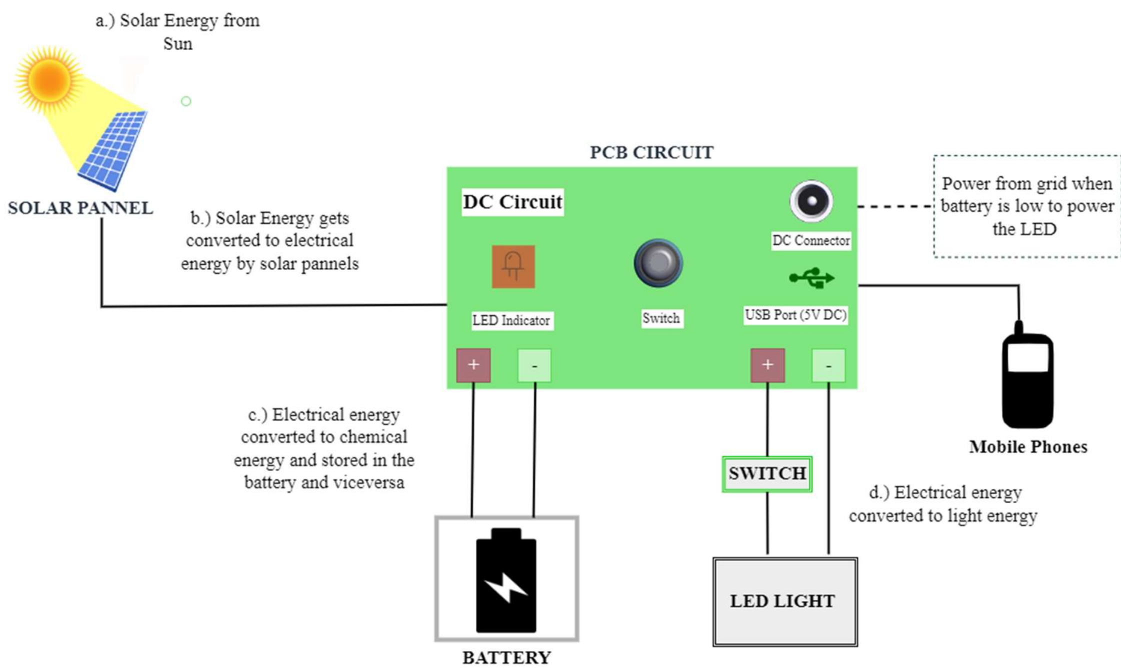

Fig. 3: The working principle of micro solar dome.

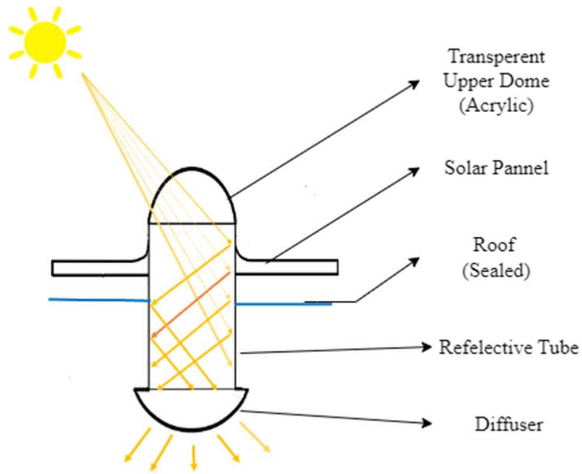

Fig. 4: Working principle of micro solar dome during daytime.

system's effectiveness, users were advised to charge their mobile phones during the day and utilize the stored energy for lighting in the evening.

Light tubes are a design solution for illuminating dark areas within houses where natural light cannot reach. The combination of windows and light pipes can enhance the influx of natural light into a space. The principle of light guiding in tubes relies on multiple reflections. These tubes incorporate highly reflective aluminum alloys. Light pipes transport light to darker sections of a home, and diffusers evenly scatter light, resembling a light source, as shown in Fig. 4. MSD includes a black opaque sheet that prevents light from entering when not required.

Research Methodology

The selection of states West Bengal, Odisha, Rajasthan, Tripura, Assam, Bihar, Manipur, and Kerala was guided by the high percentage of renewable energy installations in these areas.

Beneficiary Demographics: Most respondents engaged as daily wage laborers, primarily focused on agriculture and labor-intensive work. Male family members contributed to their livelihoods through agricultural and daily wage activities, female family members exhibiting versatility engaged in various household businesses. The demographic profile included families with school-going children. Many families resided in remote areas, highlighting the unique challenges faced in such regions.

Sampling strategy: The study adopted an operational research pattern and purposive sampling approach, targeting individuals willing to participate in the survey enthusiastically. The questionnaire incorporated open-ended and closed-ended questions to capture individuals' perceptions of post-product usage comprehensively. Around 2,500 surveys were conducted, and only 1,718 surveys were used for the analysis after data cleaning. The distribution of surveys across the study regions are (Assam: 291, West Bengal: 674, Kerala: 81, Bihar: 12, Rajasthan: 32, Manipur: 291, Tripura: 19, Odisha: 388).

Time frame considerations: The selected time frame served a strategic purpose from December 2020 to March 2022 after project implementation. Adjustments to the initial plan led to the initiation of data collection when COVID -19 lock downs restrictions eased. Despite changes, the team ensured a substantial timeframe. Respondents were required to use the product for at least six months, allowing for a comprehensive evaluation. The installers recorded demographic details and lighting conditions during installation.

Addressing data collection challenges: As installations commenced, challenges arose from COVID-19 lockdowns. When restrictions eased, community installers played a crucial role. We addressed the initial difficulties of face-to-face interviews for data collection due to strict lockdowns and language barriers by involving local NGOs for support and translation. Emphasizing the importance of community-driven partnerships during unforeseen challenges, local NGOs supported telephonic interviews.

Statistical analysis: Multinomial Logistic Regression (MLR) was chosen for its suitability in handling multiple categorical dependent variables (Rajendran et al. 2007). MLR aids in determining the likelihood of each category or response within the dependent variable. Dependent variables were divided into three groups for education and illumination levels. The analysis considered factors like awareness of renewable energy and quality of life, offering insights into their connections.

Table 1: Basic details about electricity access and kerosene usage.

Baseline questionnaire (n=1718)	Status	N [%]
Beneficiaries having access to electricity	*Yes*	1537 (89)
	No	181(10.53)
Usage of kerosene/Candle for lighting	*Yes*	1202(69.96)
	No	516(30.03)
Experienced kerosene-related accidents in past	*Yes*	19 (1.10)
	No	1699 (98.89)

RESULTS

The study revealed that lighting, driven by grid power availability, emerged as the primary electricity use in rural areas. The results indicated that a majority of the respondents, 89.5%, had access to power, while a minority of 10.5% lacked it. However, the researchers identified various factors contributing to the lack of grid power, such as illegal settlements, inability to pay, and disconnection due to non-payment of bills. Despite having access to electricity, the researchers discovered that power outages were still widespread in rural areas, especially in remote forests and hilly terrains, caused by load shedding, rainstorms, and other natural disasters. As a result, people relied on fossil fuels for lighting, with a staggering 70% of respondents using kerosene lamps, candles, lanterns, and wick lamps during power outages.

Conversely, only a tiny percentage of respondents used battery-powered lights, while others either remained in the dark or faced fewer power interruptions. Unfortunately, using fossil fuel-based lighting came with significant risks, with around 2% of respondents reporting kerosene light-based accidents. These findings underscore the critical impact of power outages on lighting sources in rural areas and the potential hazards linked to the use of fossil fuels.

Most rural households consisted of kutcha (straw roof and mud walls), semi-pucca (tin-roofed and brick-walled), and pucca houses, with insufficient illumination levels even during daylight hours. The illumination level and the type of house were cross-tabulated for better understanding. Fig. 5 depicts the type of house and illumination levels during the day based on visual observations and perceptions of beneficiaries and surveyors. The findings showed that approximately 59.4% of respondents lived in Kutcha houses, with 79.60% facing deficient illumination levels during the day and 57.4% experiencing dark or average illumination levels. About 37.0% of respondents lived in semi-pucca houses, with 20.1% facing deficient levels of illumination and 40.1% facing dark or moderate illumination levels.

In contrast, only 3.7% of respondents lived in pucca houses, indicating the minority. Those with grid electricity used bulbs or tube lights for daylight illumination, and those with access to grid-supplied electricity were careful to utilize lighting resources within the monthly subsidy. However, those with and without access to the electrical grid resorted to kerosene-based lights for illumination.

Risk Factor Analysis: Multivariate Approach

The frequency graph already depicts the electrification rate, lighting level, and kerosene usage, which may reflect the user's fundamental circumstances. Table 3 illustrates the

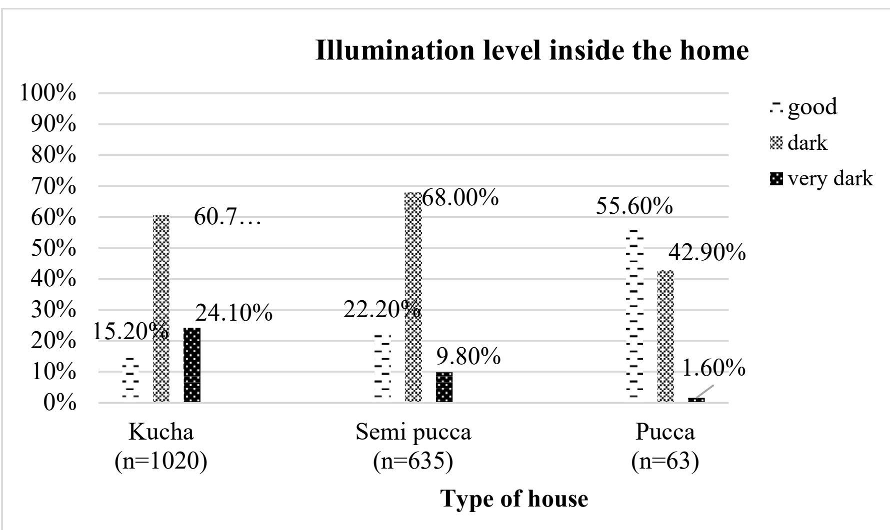

Fig. 5: Illumination level inside the house.

relationship between the risk-dependent variable MSD user education level and user perception variables concerning awareness of renewable energy. The MLR model involves categorical dependent variable (more than two) Y., e.g., three categories of education group and five explanatory (awareness about solar energy) variables X_1,X_2,X_3, X_4 and X_5 (Table 1) and three categories of illumination level inside the house before the MSD installation group and four explanatory (quality of life) variables X_1,X_2,X_3 and X_4 (Table 2).

The exploration of user variables, such as actual illumination level inside the house, safety, increase in education hours of the children, and engagement in economic activities, extended to the user's change in household illumination level after the installation. The categorization included good, dark/average, and very dark illumination levels. The coding for all variables was as follows: 1 for agree, 2 for disagree, and 3 for no knowledge, as presented in Table 2.

It is interesting to note that households with darker illumination conditions experienced a fourfold increase in the expected change in illumination levels after the installation (3.93(2.16-7.16); $p < 0.001$), indicating that the product was crucial in improving the lighting conditions in households that need it the most. The household with good illumination did not require additional lighting significantly for safety during the dark (n=331). The households with dark illumination levels (n=1016) have experienced a significant increase in their perception of safety after installing the MSD (6.07(4.03-9.14); $p < 0.001$), demonstrating the significant impact it has had on their lives. In households with good illumination levels, children's education studying hours were drastically increased ($p < 0.001$), and there was no expected change in illumination level ($p < 0.001$) when compared to very dark illumination with each factor. The household having dark illumination perceived a significant increase in time spent on children's education (5.72 (4.01-8.16); $p < 0.001$), providing them with the opportunity to receive a better education, and children also said, "Our eyes are no longer burning".

Awareness Level of Clean Energy Technologies After Installation

The user's education level was explored for other varia-

Table 2: The illumination level's effect on the quality of life.

Illumination level Factors	Status	No [%]	B±SE	Exp(β)95%CI	p-value
Good (n=331)		*Intercept*	-2.58 ± 0.43		
Productivity	Agree	126 *(38.07))*	0.93 ± 0.25	2.53(1.57-4.1)	< 0.001
	Disagree	205 *(61.94)*	*Reference*		
Safety& Security	Agree	187 (56.5)	-1.02 ± 0.23	0.37(0.23-0.57)	< 0.001
	Disagree	144 (43.51)	*Reference*		
Education	Agree	116 (35.05)	3.69 ± 0.29	39.86(22.69-70.04)	< 0.001
	Disagree	193 (58.31)	5.07 ± 0.41	157.98(71.7-348.1)	< 0.001
	Neutral	22 (6.65)	*Reference*		
Changes in illumination level	Agree	184 (55.59)	0.03 ± 0.36	1.03(0.51-2.05)	0.951
	Disagree	120 (36.26)	2.01 ± 0.4	7.39(3.39-16.12)	< 0.001
	Neutral	27 (8.16)	*Reference*		
Dark /Average (n=1078)		*Intercept*	-2.88 ± 0.37		
Productivity	Agree	377 (34.97)	0.88 ± 0.22	2.4(1.58-3.64)	< 0.001
	Disagree	701 (65.02)	*Reference*		
Safety & Security	Agree	1018 (94.43)	1.81 ± 0.21	6.07(4.03-9.14)	< 0.001
	Disagree	60 (5.56)	*Reference*		
Education	Agree	495 (45.91)	1.75 ± 0.19	5.72(4.01-8.16)	< 0.001
	Disagree	307 (28.47)	2.9 ± 0.33	18.01(9.51-34.08)	< 0.001
	Neutral	276 (25.60)	*Reference*		
Changes in illumination level	Agree	747 (69.29)	1.37 ± 0.31	3.93(2.16-7.16)	< 0.001
	Disagree	295 (27.36)	2.45 ± 0.36	11.52(5.78-22.98)	< 0.001
	Neutral	36 (3.33)	*Reference*		
Very dark (n= 309)			*Reference category*		

$p<0.05$ = statistically significant

bles like the importance of off-grid during cyclone/disaster, electricity access equivalent to health care and education, the possibility of off-grid replacement options to grid electricity, and The MSD helping realize the necessities of life. All variables were coded categorically: 1 = agree, 2 = disagree, 3 = no knowledge. The user education was coded as 1= uneducated, 2= primary to higher secondary, and 3=graduation, as shown in Table 3.

Users without any formal education lacked prior knowledge about solar energy ($p < 0.001$) and believed that access to electricity was equivalent to access to health care and education (3.9 (1.28-11.88); $p < 0.017$). Interestingly, they also firmly believed that MSDs should replace other electrification options in remote areas (29.75(5.9-150.01); $p< 0.001$). On the other hand, respondents with a higher secondary level of education had significantly different beliefs. They considered electricity access to be equivalent to access to health care and education and believed that the Solar Dome could facilitate the realization of basic necessities of life in case of no electricity connectivity

Table 3: Education level on awareness level following the implementation of cleaner technologies.

Awareness factors	Status	No [%]	B±SE	Exp(β)95%CI	p-value
Uneducated (n=1106)	Intercept		1.44 ± 0.88		
Electricity is equivalent to access to health care and education	Agree	748(67.64))	1.37 ± 0.57	3.9(1.28-11.88)	0.017
	Disagree	129(11.67))	-0.88 ± 0.6	0.42(0.14-1.33)	0.14
	Neutral	229(20.71))	*Reference*		
Solar Dome facilitates the realization of necessities of life	Agree	803(72.61))	0.79 ± 0.47	2.19(0.88-5.5)	0.096
	Disagree	132(11.94))	0.03 ± 0.53	1.03(0.38-2.85)	0.961
	Neutral	171(15.47))	*Reference*		
MSD can help during cyclones/disasters	Agree	578(52.27))	0.12 ± 0.66	1.13(0.32-4.02)	0.861
	Disagree	327(29.57))	1.54 ± 0.89	4.65(0.83-26.15)	0.082
	Neutral	201(18.18))	*Reference*		
Prior knowledge of solar energy	Agree	157(14.2))	-4.45 ± 0.7	0.02(0.01-0.05)	< 0.001
	Disagree	949(85.81))	*Reference*		
MSDS should replace other electrification options	Agree	828(74.87))	3.4 ± 0.83	29.75(5.9-150.01)	0.001
	Disagree	178(16.1))	1.8 ± 0.81	6.04(1.25-29.17)	0.026
	neutral	100(9.05))	*Reference*		
Education (1- 12th)	Intercept		1.49 ± 0.88		
Electricity is equivalent to access to health care and education	*Agree*	390(67.48))	2.35 ± 0.58	10.47(3.37-32.5)	< 0.001
	Disagree	90(15.58))	0.32 ± 0.6	1.38(0.43-4.39)	0.596
	Neutral	98(16.96))	*Reference*		
Solar Dome facilitates the realization of basic necessities of life	Agree	315(54.5))	0.08 ± 0.48	1.08(0.43-2.72)	0.872
	Disagree	112(19.38))	-0.07 ± 0.52	0.94(0.34-2.58)	0.894
	Neutral	151(26.13))	*Reference*		
MSD can help during cyclones/disasters	*Agree*	362(62.63))	0.49 ± 0.67	1.63(0.45-5.92)	0.465
	Disagree	150(25.96))	1.62 ± 0.89	5.04(0.89-28.79)	0.069
	Neutral	66(11.42))	*Reference*		
Prior knowledge of solar energy	Agree	116(20.07))	-4.02 ± 0.7	0.02(0.01-0.08)	< 0.001
	Disagree	465(80.45))	*Reference*		
MSDS should replace other electrification options	Agree	397(68.69)	1.72 ± 0.83	5.58(1.12-27.96)	0.037
	Disagree	67(11.6))	0.69 ± 0.81	1.99(0.41-9.62)	0.397
	neutral	114(19.73))	*Reference*		
Graduation (n=34)			Reference category		

$p<0.05$ = statistically significant

(10.47(3.37-32.52); $p < 0.001$). Many users had no prior knowledge about solar energy (0.02 (0.01-0.08); $p < 0.001$), and they held a significant belief that MSDs should replace other electrification options like solar energy ($p = 0.037$) in remote areas.

DISCUSSION

Solar energy has revolutionized meeting energy demands and enhancing the quality of life in regions with restricted electricity access. The introduction of solar lanterns has led to significant changes in lighting patterns, with households switching from traditional lighting sources to solar lanterns, resulting in higher levels of satisfaction and economic development opportunities (Adkins et al. 2010). However, despite the many benefits of solar energy, not all studies have shown significant improvements in socioeconomic outcomes. The randomized field trial conducted in Uttar Pradesh's Barabanki area showed that while the provision of solar lights to unelectrified families did not result in significant improvements in development, the research on the socioeconomic and behavioral effects of solar lanterns suggests that they have the potential to provide significant marginal benefits to marginalized populations (Aklin et al. 2017). While solar lanterns may not lead to immediate, measurable socioeconomic improvements, they can still improve the lives of those living in rural communities. As such, future research should continue to investigate the potential benefits of solar lanterns on households' daily behavior, well-being, and perceptions of solar lighting rather than examining the high economic effects (Mahajan et al. 2020). While previous studies extensively examined the impact of solar home systems and off-grid setups in rural areas, only some researchers have prioritized analyzing solar lanterns as the focal point of their investigations. The MSD, used in this study, is a unique product that employs vertical light pipes, one of the most common renewable energy sources used in daylight science and daylighting technology to provide daylight illumination (GhoshThakur et al. 2022). This study has examined the impact of the Micro Solar Dome on economic activities, children's education hours, safety, and awareness of renewable energy technologies.

By focusing on this innovative and versatile product, this research sheds light on a new aspect of solar technology that researchers still need to explore fully. The study's findings showed a concerning situation with lighting in rural homes. It was alarming that these homes did not have enough light even during the day because they kept their windows closed to prevent insects and snakes from coming in. People also restricted electricity use because they feared surpassing the government's free unit allocation. This emphasizes the significance of seeking alternative solutions to enhance indoor conditions without increasing household energy expenses. The installation of MSDs has effectively addressed this issue. These energy-saving devices have proven effective in providing high luminance flux, resulting in improved lighting conditions inside the home. The installations primarily targeted the kitchen, common room, and cattle-rearing spaces—key areas necessitating consistent daylight illumination. The study further unveiled that approximately 55% of households observed a significant enhancement in illumination following the light pipes' installation. In most households surveyed, women remained at home while male members were involved in agricultural activities or daily wage labor.

With adequate lighting, women felt safer and more secure while doing household chores. However, the grid supply in rural areas was highly intermittent, and power interruptions at night left women feeling vulnerable and forced to rely on kerosene lamps or candles for lighting. The installation of the MSD during the pandemic has been a boon for rural households. It has supported women in carrying out their household chores without any hassles, and the light provided by the MSD has been available from morning until late evening, making them feel safer and more secure, which has been reported in previous studies related to solar technologies (Buragohain 2012, Grimm et al. 2016, Urpelainen 2016). Women often engage in small-scale economic activities such as sewing, weaving, and shopkeeping. However, limited lighting availability has consistently posed an obstacle, constraining their working hours to daylight only. The installation of the MSD has changed this scenario drastically.

Women can now work in the evening, especially in households with low illumination levels, leading to a significant increase in hours spent on economic activities ($p < 0.001$) post-installation. This increase translates into economic benefits for the household and may contribute to women's empowerment. With access to affordable and reliable energy, women can extend their working hours, which reduces gender-related drudgery and enhances their socioeconomic status, as reported in previous studies related to gender implications of energy access (Winther et al. 2018). School-going children have also benefited greatly from the MSD installation. The children's academic performance was not assessed in the study. Still, the increase in education hours has been perceived by the children using it for reading during their late evening hours, which has been reported in previous studies related to solar lanterns and children education (Sharma et al. 2019). Furthermore, with online education becoming the norm during the pandemic, children continued their studies using mobile phones. The installation of the MSD has enabled them to charge their mobile phones and extend their study hours into the evening.

Empowering Minds: Illuminating Community Awareness

MSD as an alternative to conventional energy sources has garnered significant attention recently. The study aimed to evaluate respondents' perceptions regarding the viability of MSDs as an alternative to traditional electrification options in areas prone to cyclones and natural disasters, along with their views on the importance of electricity access to health and education. The respondents were classified based on their formal education levels. Before the installation of MSDs, many respondents had limited knowledge of solar energy and its potential benefits. However, after the installation, our study revealed a significant increase in awareness of renewable energy among marginalized communities. The MSD facilitates the realization of basic life necessities in the absence of electricity connectivity. Respondents also strongly believed that off-grid products like MSDs could assist them during cyclones and other natural disasters, which often affect coastal areas.

Surprisingly, the level of education did not significantly impact the adoption of solar energy among respondents. While some previous studies have suggested that education plays a significant role in solar adoption. Our findings also align with previous work indicating that other contextual factors, such as social perception of electricity, may be more influential (Etongo & Naidu 2022). MSDs emerge as promising solutions for sustainable advancement, particularly within rural contexts. They replace harmful kerosene lamps, reduce indoor pollution and improving health.

Additionally , these technologies contribute to reducing carbon emissions, aligning with global climate change initiatives. The scope of this initiative extends beyond mere technological implementation, it encompasses key considerations such as prioritizing user-friendliness, ergonomic design, and alignment with local customs as mentioned in the previous studies (Balls 2020). Furthermore, these technologies possess the potential to stoke interest and pave the way for scaling up solar capacity within homes, ultimately fostering a transition toward grid independence. As these dynamic forces coalesce, they chart a trajectory toward a more sustainable and empowered future for rural communities. However, it is essential to also consider the economic, financial, and policy aspects due to their potential to promote economic growth via local entrepreneurship and lower energy costs. These aspects also interact with supportive policies, financial models, and affordability, all contributing to advancing sustainable energy transitions.

Policy Recommendations

This study underscores several key policy recommendations for enhancing the adoption of solar energy solutions in marginalized communities. Foremost among these is promoting community-based solar initiatives, which is vital for fostering a sense of ownership and collaboration. Establishing local support networks can significantly facilitate the collective adoption of solar solutions, making them more accessible and sustainable. Furthermore, the development and deployment of educational and awareness programs are essential. These programs, focusing on raising awareness about the benefits of solar energy, dispelling prevalent myths, and providing practical knowledge on sustainable energy practices, are crucial. Without this foundational awareness and education, merely providing the products would not be as effective. It is vital to ensure that communities are not only equipped with solar technology but also educated about its use and benefits. Lastly, it is crucial to formulate policies specifically tailored to address marginalized communities' unique challenges and needs, thus ensuring equitable access to clean energy resources.

Limitations

While our study has contributed valuable insights into the adoption of solar energy among marginalized communities, it is essential to acknowledge some limitations. Firstly, although the product used in our study was innovative as it could be used both day and night, we could not capture the reduction in kerosene usage as many households still needed firewood stoves for cooking. Additionally, due to COVID-19 restrictions, we could not conduct spot validations in many homes to verify reported increases in income and instead relied on self-reported perceptions. Despite these limitations, our study provides valuable insights into the potential benefits of solar adoption and highlights areas for further research and improvement.

CONCLUSION

The MSD has demonstrated its effectiveness in enhancing the quality of life in rural areas, particularly among marginalized communities. The study has shown that MSD implementation leads to better illumination, increased household safety, extended study hours for children, and expanded economic activities. The positive perception of the people highlights the significant benefits that MSDs offer. A crucial finding of this research is the role of education in fostering the adoption of solar energy technologies, with focus on hands-on experience is critical in enhancing understanding and encouraging the use of solar products. The accessibility of MSDs as affordable and sustainable energy solutions enables these communities to meet their energy needs independently and reduce reliance on traditional fossil fuels. This research contributes significantly to setting realistic expectations for what can be achieved with basic access to clean energy. It underscores the value of incremental steps towards sustainable energy solutions in rural settings instead of pursuing overly ambitious goals requiring extensive social and economic overhaul. The success of installing MSDs in marginalized communities is a pivotal step in introducing and fostering interest in green energy technologies. In light of these findings, the study advocates for the replication and expansion of similar projects, reinforcing the belief that small-scale, community-centric initiatives can profoundly impact the quality of life in rural households by providing accessible, affordable, and sustainable energy solutions.

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