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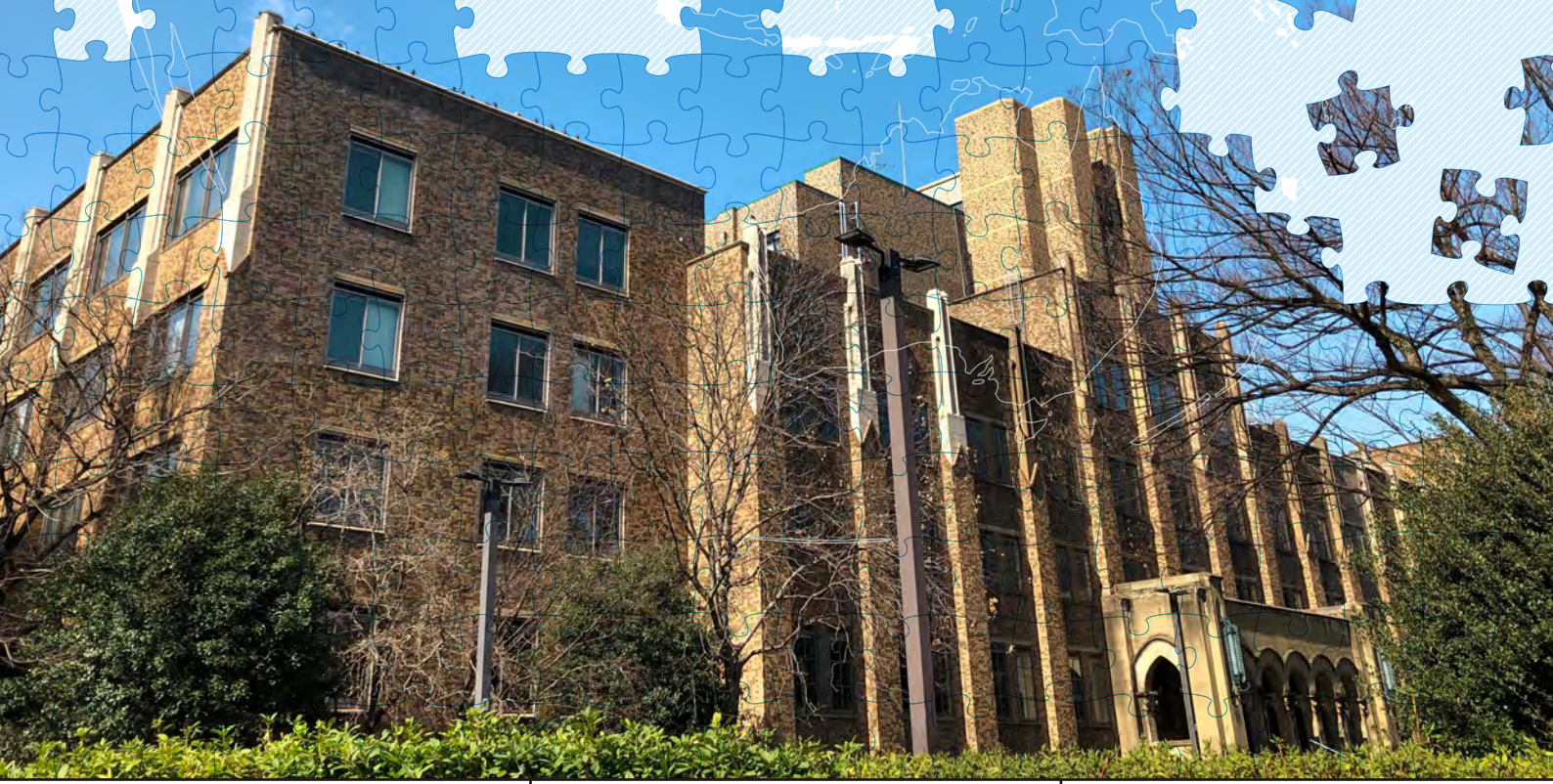
From Darkness to Radiance: A Study on the Health Impact of Solar Energy Usage in Off-Grid Households



No. 104
Date November.2024
SDGs 7 AFFORDABLE AND CLEAN ENERGY

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From Darkness to Radiance: A Study on the Health Impact of Solar Energy Usage in Off-Grid Households

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Abstract: Solar energy, an option for off-grid energy supply, is often adopted as a solution to limited national grid power supply. The households that use solar energy option have more access to electricity compared to the traditional electric supply-based households so this facility is supposed to increase welfare for households. However, the evidence of the impact of solar energy usage is limited. This study considers vulnerable off-grid households of Kenya as units of analysis, using instrumental variable as identification to examine the impact of solar energy usage on health outcomes, considering gender based heterogeneity. We used dataset prepared by Oxford Policy Management Limited (2021), who conducted Randomized Control Trial in which bi-monthly cash top-up is considered as the treatment variable and solar energy usage is considered as one of the outcomes. In this study, bi-monthly cash top-up (a subsidy) is taken as an instrumental variable and usage of solar energy is the treatment variable. The findings show that the usage of solar energy decreases the health expenditure of user households by 26 percent, indicating better health condition. Heterogeneous analysis shows that solar energy usage has more positive impact on health of female than male members.

Key-words: Solar Energy, Clean Energy, Health, Solar Home System, Gender Based Heterogeneity

1. Introduction:

1.2 Background:

Energy poverty, a pervasive challenge representing a condition in which households are unable to access the minimum energy services necessary to fulfill their biological and social needs, has profound implications for household welfare (Bouzarovski & Petrova, 2015; Hammerle & Burke, 2022). The ability to address and overcome energy poverty is integral to achieving Sustainable Development Goal (SDG)-7, that emphasizes the need to ensure access to sustainable and affordable energy for all. However, this goal remains elusive for many developing countries, with a staggering 674 million people worldwide still lacking access to electricity, as reported by Pan et al. (2021). Amidst this global challenge, solar energy has emerged as a promising alternative energy source and a strategic policy tool to attain the objectives outlined in SDG-7. Solar energy, designed to provide off-grid energy supply, have gained traction as a viable solution to mitigate the limitations of national grid power supply and, consequently, reduce energy poverty. The effectiveness of such systems is particularly significant in the context of Africa, where 56% of households currently lack access to electricity (Berahab, 2022).

Remarkably, Kenya, situated in the heart of Africa, presents a unique energy landscape. While the energy crisis is a widespread issue on the continent, affecting over half of African households, Kenya stands out with a comparatively lower level of energy deprivation, impacting only 25% of its households (Ayhan & Jacob, 2021). The nation has made substantial strides in promoting renewable energy sources, with approximately 73% of its effectively installed power generation derived from renewable sources (Sai & Lin, 2022). This places Kenya among the cleanest global energy producers, signaling a commitment to sustainable and environmentally friendly energy solutions. Furthermore, Kenya's geographical location near the equator grants it substantial solar

energy potential, with an average daily 4 to 6 kWh/m2solar irradiance, which translates into an impressive 250 million tons of oil equivalent (Takase et al., 2021). Notably, 1.2% of Kenyan households currently harness solar energy for various purposes, including lighting, mobile charging, and powering televisions. The seventh UN Sustainable Development Goal (SDG 7) emphasizes ensuring clean, sustainable, and affordable energy that are vital for improving health (SDG 3) because unclean energy jeopardizes health due to air pollution (Li et al.,2023).

Additionally, the solution to energy poverty is recognized as a pivotal policy question due to its adverse impact on household health conditions, as documented by Liddell and Morris (2010) and Howden-Chapman et al. (2012). Households grappling with energy poverty are more susceptible to various health challenges, including isolation, depression, asthma, and increased reliance on health services (Thomson and Snell, 2013). Women are considered as the worst sufferer of unclean energy usage resulting from energy poverty. Additionally, a study by Li et al. (2023) contended that the utilization of unclean energy usage contributes to increase depression among women. Conversely, Liu et al. (2022) posited that the use of unclean energy is linked to an increased incidence of hypertension among women who experience heightened exposure to indoor air pollution. Further, unclean energy usage is associated with a 4% more maternal mortality (Wang et al., 2019). In this context, solar energy emerges as a beacon of hope for addressing these interconnected challenges. Solar energy is considered a clean and renewable energy source, and its adoption is expected to improve air quality, subsequently improving public health conditions (Wiser et al., 2016). However, despite these theoretical expectations, empirical evidence on the actual impact of solar energy remains scarce and inconclusive.

This study conducts a comprehensive examination of gender based heterogeneous causal impact of solar home system usage on the health outcomes of vulnerable households in Kenya. The focus

will be on households that lack access to on-grid electricity supply, specifically those in the Kilifi and Garissa regions identified as energy poverty-afflicted. These regions are characterized by a lack of access to conventional electricity sources, making them suitable units of analysis for understanding the impact of solar energy adoption. It is crucial to acknowledge that households actively choose to install and use solar home systems, making the usage of solar energy an endogenous variable. Any comparison between those using solar energy and those who do not may induce self-selection bias unless the endogeneity of solar energy usage is appropriately addressed. To mitigate this bias, instrumental variable (IV) analysis is employed as an identification strategy. However, IV analysis necessitates that the instrumental variable satisfies conditions of exogeneity, relevance, and exclusion restriction (Baiocchi et al., 2014).

We used dataset prepared by Oxford Policy Management Limited (2021), who conducted Randomized Control Trial in which bi-monthly cash top-up is considered as the treatment variable and solar energy usage is considered as one of the outcomes. In this study, bi-monthly cash top-up (a subsidy) is taken as an instrumental variable and usage of solar energy is the treatment variable. This study focuses on vulnerable off-grid households in Kilifi and Garissa, Kenya. The 'Mwangaza Mashinani' project in Kenya plays a crucial role in this research, offering a bi-monthly cash subsidy to assist vulnerable households in repaying Solar Home System (SHS) costs over one year. The subsidy is strategically designed to make SHS more affordable to vulnerable households, and its provision is contingent upon the households' commitment to purchasing a three-bulb SHS with a USB charging point on a pre-paid payment basis. In this study, the offer of a bi-monthly cash top-up (subsidy) is considered as an instrumental variable, effectively increasing the usage of solar energy among vulnerable households.

The findings of this study are anticipated to provide valuable insights into the significance of attaining access to clean energy, particularly through the adoption of solar energy. By examining the impact of solar energy usage on household welfare, specifically in terms of health outcomes, this research aims to contribute to the ongoing discourse on sustainable energy access and its multifaceted implications for public health in the context of developing countries. In summary, this study represents a comprehensive effort to explore the impact of solar energy usage on the health outcomes of vulnerable households in Kenya, employing a rigorous research design and addressing key research gaps in the existing literature.

1.2 Literature Review

Some studies have explored the association between clean energy usage and health outcomes. Raihan et al. (2022) reported a positive correlation between clean energy usage and public health expenditure using Dynamic Ordinary Least Squares, but this correlational approach cannot establish causality. Similarly, Iorember et al. (2022) employed panel quantile regression to argue for a negative correlation between energy use and health outcomes. Saleem et al. (2022) utilized a panel vector auto-regression econometric approach to examine the association between non-renewable energy and health expenditure. Shang et al. (2022) applied a cross-sectional augmented approach to evaluate the association between renewable energy usage and health expenditures.

Some studies examined gendered perspective on energy usage. Winther et al., (2018) examined how energy usage has gender based disparity, arguing that solar energy enhance empowerment of women. Similarly, Buechler et al., (2020) argue that old women suffer more because of energy poverty. Further, Shiradkar et al., (2023) argue that women empowerment can enhance from a solar energy initiative offering training and skill development opportunities. Bell et al., (2020) provided a feminist energy theory combining the political, economic, socio-ecological and

technological factors. Stock and Birkenholtz (2020) examined the impact of solar energy on women empowerment based on a framework of feminist political ecology. Pearl-Martinez (2020) explored that gender based inequality in energy access needs to be addressed.

Few studies examined gender based health impact of clean energy usage. Ding et al., (2014) argue that clean energy usage change gender based roles and decreases possibility of respiratory diseases of women. Further, Li et al., (2023) argue that clean energy usage decrease depression of women. Wang et al., (2019) argue that clean energy adoption decrease mother mortality by 4%. Similarly, Li et al., (2022) examined how access to clean energy improves women health through improving indoor air quality. Liu et al., (2022) argue that unclean energy usage increase hypertension among women who are more exposed to indoor air pollution. Together, these studies highlight the multifaceted benefits of clean energy adoption, ranging from altering gender roles to improving mental health, reducing maternal mortality, and enhancing overall well-being through better indoor air quality.

Despite the significant contributions of previous studies, three critical research gaps persist. First, the impact evaluation of clean energy on health outcomes remains inconclusive. Second, no previous studies have systematically examined the causal impact of solar energy on household health outcomes. Third, there is a lack of research investigating gender based heterogeneous impact of solar energy, taking into gender disparity framework.

2. Materials and Methods

2.1 Data Description:

The dataset of the study is adapted from the dataset collected by Oxford Policy Management Limited (2021). The original dataset is collected to evaluate the impact of the Mwangaza Mashinani project, which aims to increase energy access for the most vulnerable off-grid households with school-going children in Kenya. Kilifi and Garissa are the selected area of the study that has been depicted in Figure 1. The households are sampled using stratified random sampling. The 567 households were randomly assigned to receive the offer to subsidy, whereas 547 were randomly assigned not to receive the offer to subsidy. Baseline data was collected from February 2019 to April 2019, midline data was collected from July 2020 to August 2020 and the end line data was collected from April 2021 to June 2021. The treatment assigned group was offered to receive total 13100 KSH divided as bi-monthly top up for a year to pay the cost of SHS. This study considers 7872 individuals belonging to the 1147 households to examine the impact of solar energy usage on their health outcomes. The treatment variable solar energy usage is determined based on whether the household use solar energy for lighting purpose or not.

2.2 Summary Statistics

Table 1 reports the summary statistics of the members of the households based on solar energy. The table shows that 59.55% of the households are non-users of solar energy and 40.45% of the households are users of solar energy. Gender of user and non-user are quite on average same. Average age of the non-users is 25.41 years whereas average age of users is 24.83 years. Monthly health expenditure is measured in Kenyan Shilling (KES) (USD 1=KES106 in study period). Average health expenditure of non-users is much more than that of users. Average incidence of cold related disease, respiratory disease, cold fever and burning incidence of non-users are higher than those of users.

Table 1: Summary statistics: Based on Usage of SHS

	Mean	Standard Deviation	Number of Observations
Non-Users (Solar Energy)			
Gender (Member)	0.54	0.50	4662
Age (Member) in Years	25.41	23.43	4662
Health Expenditure (KES)	74.30	568.00	4662
Cold related Disease	0.09	0.29	4662
Respiratory Disease	0.01	0.11	4662
Cold Fever	0.05	0.22	4662
Fever not related to cold	0.05	0.21	4662
Burn Incidence	0.01	0.09	4662
Users (Solar Energy)			
Gender (Member)	0.54	0.50	3210
Age (Member) in Years	24.83	22.20	3210
Health Expenditure (KES)	53.13	340.51	3210
Cold related Disease	0.08	0.28	3210
Respiratory Disease	0.01	0.09	3210
Cold Fever	0.04	0.20	3210
Fever not related to cold	0.05	0.23	3210
Burn Incidence	0.01	0.08	3210

2.3 Methodology:

Usage of solar energy suffers from endogeneity problem that biases estimation of the causal impact. Even experimental studies can be affected (Sajons, 2020). To tackle this challenge head-on, our study employs the instrumental variable approach that estimates local average treatment effect through addressing confounding issues (Lousdal, 2018). An instrumental variable is related to the treatment, but neither is it related to any confounder because of being randomized, nor has it any causal pathway to the outcome other than through the treatment (Burgess et al.,2017). In our study, the selected instrumental variable is the offer to pay a bi-monthly cash top-up, serving as a subsidy to incentivize and facilitate solar energy usage among households. This subsidy, integral to the

'Mwangaza Mashinani' project in Kenya, strives to enhance SHS accessibility for energy poverty-afflicted households. To meet the exogeneity condition fundamental to instrumental variable analysis, the bi-monthly cash subsidy offer is given on a random basis. This randomness ensures that the offer remains unrelated to any potential confounding variables, mimicking the characteristics of a randomized control trial (RCT). This design feature significantly mitigates the endogeneity problem associated with self-selection biases in solar energy adoption. The relevance condition, another pivotal criterion, is satisfied by the expected substantial impact of the bi-monthly cash subsidy offer on SHS usage. By making solar energy more economically viable, households are anticipated to be more inclined to adopt and actively utilize this cleaner energy source. Lastly, the exclusion restriction condition is met, ensuring that the offer of a bi-monthly cash subsidy has no direct impact on health expenditure, except through its indirect influence on solar energy usage. This condition safeguards the validity of the instrumental variable, assuring that its impact is solely transmitted through its effect on the treatment variable without introducing additional pathways that could confound the relationship.

By leveraging bi-monthly cash subsidy as the instrumental variable, our study endeavors to unravel the intricate relationship between solar energy usage and health outcomes among vulnerable households in Kilifi and Garissa, Kenya (Figure 1). This meticulous methodology not only fortifies the internal validity of our findings but also ensures that the evidence generated directly addresses the causal impact of solar energy adoption on health, closely aligning with the overarching objective of our study.

Two-stage least square estimation is applied in an instrumental variable setting. In this study, the following first-stage equation is used:

$$S_i = a_0 + \pi T_i + \mu_i$$

Here, $\boldsymbol{S}_i$ is the treatment, solar energy usage, that is a binary variable equals to 1 if the household uses SHS; it equals to 0 if otherwise. $\boldsymbol{T}_i$ is the instrumental variable that equals to 1 if the household received offer for Top-up and it equals to 0 if otherwise.From the first stage estimation predicted $\boldsymbol{S}_i$ is measured and then the below mentioned second stage equation to examine the local average treatment effect:

$$X_i = \beta_0 + \rho_c \hat{S}_i + \varepsilon_i$$

$\boldsymbol{X}_i$ are the outcome variables, health condition indicators. Here, ρ_c is the local average treatment effect of solar energy usage. $\widehat{\boldsymbol{S}}_{\boldsymbol{i}}$ is the predicted solar energy usage. ρ_c is the main treatment effect of solar energy on diverse health outcomes household level.

3. Results and Analysis

3.1 Main Results

Table 2 reports the first stage result. The first stage result shows that Top-up offer enhance solar energy usage by 54%. The strong impact of Top-up offer on solar energy demonstrates relevance of Top-up offer as the Instrumental Variable.

Table 2: Impact of the Offer and on Solar Energy Adoption

VARIABLES	(1) Solar Energy Usage (0/1)
Top Up Offer	0.54***
	(0.01)

Notes: Significance levels where $*$ for $p < 0.10$, $**$ for $p < 0.05$, and $***$ for $p < 0.01$.

Table 3 reports the impact of solar energy usage on health conditions. The result shows that solar energy improves the health condition of the household members significantly. SHS decreases health expenditure of individual household members by 26.70%. Then solar energy decreases the

incidence of cold problem, breathing problem and cold related fever significantly. However, solar energy has no conclusive impact on incidence of burn.

Table 3: Impact of Solar Energy on Health Outcomes

VARIABLES	(1) Log of Health Expenditure	(2) Cold (0/1)	(3) Breathing (0/1)	(4) Cold related Fever	(6) Incidence of Burn
Solar Energy	-0.267***	-0.0292**	-0.0159***	-0.0214**	-0.00410
	(0.0779)	(0.0127)	(0.00458)	(0.00941)	(0.00387)
Constant	0.627***	0.0993***	0.0170***	0.0548***	0.00917***
	(0.0373)	(0.00607)	(0.00220)	(0.00451)	(0.00185)
Observations	7,828	7,872	7,872	7,872	7,872

Notes: Significance levels where $*$ for $p < 0.10$, $**$ for $p < 0.05$, and $***$ for $p < 0.01$.

3.2 Heterogeneous Impact Analysis

Table 4 reports the impact of solar energy on health conditions based on gender. The result shows that solar energy usage improves the female health condition of the household members significantly. Solar energy usage decreases female health expenditure by 30.80%. Then solar energy usage decreases the incidence of cold problem, breathing problem and cold related fever of female members significantly. However, solar energy usage has no conclusive impact on incidence of burn of female members. The result shows that solar energy usage has significant impact on only health expenditure of male members. Solar energy usage decreases male health expenditure by 28.60% at 5% significance level. However, solar energy usage has no conclusive impact on the incidence of cold problem, breathing problem, cold related fever and burn of male members.

Table 4: Heterogeneous Impact Based on Gender

Outcomes	Only Female	Only Male
Log of Health Expenditure	-0.308***	-0.286**
	(0.118)	(0.114)
Cold Problem (0/1)	-0.0534***	-0.00182
	(0.0190)	(0.0188)
Breathing Problem (0/1)	-0.0297***	-0.00748
	(0.00755)	(0.00599)
Cold related Fever	-0.0311**	-0.0128
	(0.0144)	(0.0135)
Incidence of Burn	-0.00433	-0.00562
	(0.00630)	(0.00530)

Notes: Significance levels where $*$ for $p < 0.10$, $**$ for $p < 0.05$, and $***$ for $p < 0.01$.

Table 5 reports the impact of solar energy usage on health conditions based on literacy status. The result shows that solar energy usage has better impact on literate individuals, reducing health expenditure, the incidence of cold problem, breathing problem and cold related fever. Solar energy usage decreases health expenditure by 27.00%. However, solar energy usage has no conclusive impact on the incidence of burn of literate members. Health expenditure of illiterate individuals decreases by 63.70% as a result of using solar energy. Further, cold related fever of of illiterate individuals also decreases significantly for solar energy users. However, solar energy usage has no conclusive impact on the incidence of cold problem, breathing problem and burn of illiterate individuals.

Table 5: Heterogeneous Impact Based on Educational Status

Outcomes	Only Literate	Only Illiterate

Log of Health Expenditure	-0.270***	-0.637***
	(0.0944)	(0.225)
Cold Problem (0/1)	-0.0295**	-0.0252
	(0.0145)	(0.0372)
Breathing Problem (0/1)	-0.0115**	-0.0259*
	(0.00511)	(0.0156)
Cold related Fever	-0.0254**	-0.0582**
	(0.0108)	(0.0288)
Incidence of Burn	-0.000582	-0.00577
	(0.00511)	(0.0103)

Notes: Significance levels where $*$ for $p < 0.10$, $**$ for $p < 0.05$, and $***$ for $p < 0.01$.

3.3 Placebo Outcome Test

One of the falsification tests of instrumental variable set up is to conduct an analysis with placebo outcomes like pretreatment outcomes. If placebo outcomes are significant, the validity of instrumental variable will be questionable. Table 6 shows analysis of the impact of top-up on placebo outcomes and shows that no outcome is significant, suggesting strength of top-up as an instrumental variable. This test also gives evidence to Top-up fulfills exogeneity condition as an instrumental variable.

Table 6: Placebo Outcome Test

	(1)	(2)	(3)
VARIABLES	Gender of the Member	Literate or Not	Number of Working Members
Offer to Subsidy	0.0151	8.725	-11.46
	(0.0223)	(9.944)	(22.33)

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

4. Discussion:

The study reports that solar energy decreases health expenditure, the incidence of cold problem, breathing problem and cold related fever of vulnerable households, indicating improvement in household level health conditions. The reasons of the impact of solar energy usage on health expenditure can be multifarious. SHS improves the health expenditure of the households through reduction of the Kerosene (Wagner, 2021) as Kerosene leads to extreme respiratory diseases of small children (Lemaire, 2018) and Kerosene lead to more burns (Ahuja, 2011). Solar energy usage reduces unclean energy sources that have significant negative impact on health conditions (eg, arthritis and osteoporosis) among aging people (Smith et al., 2023). Solar energy usage improves health condition of households as solar energy usage decreases pollution, improves light quality, increases duration of light in the evening and reduces work on cleaning kerosene lamps (Mondal & Klein, 2011). This study has a policy implication for the energy policy makers, suggesting increase in clean energy usage by the means of solar energy usage can improve the household health condition, especially women.

Heterogeneity analysis shows that solar energy improves female health condition significantly, whereas its impact on male counterparts is less conspicuous. One of the reasons of heterogeneous gender based impact is that female members spend more time in the house and female members are more exposed to energy usage. Female members are more exposed to usage of unclean energy sources and solar energy improves female health through decreasing their access to unclean energy sources. Padonou (2022) argue that solar energy usage can improve women health through reducing their unpaid work like collection of unclean fuel like firewood. Solar energy usage can lessen the exposure of women to indoor smoke pollution, consequently decreasing the possibility of respiratory diseases in women (Ding et al., 2014). Improvement of air quality through reducing

unclean energy usage, solar energy usage provides a healthy home environment that improves woman health (Li et al., 2022).

Our finding is consistent with Raihan et al. (2022) who reported clean energy usage reduce public health expenditure. However, Iorember et al. (2022) found a negative correlation between energy use and health outcomes. The difference of outcome with Iorember et al. (2022) is understandable from the fact that we used solar energy usage that is a clean energy source but the former study focused on both clean and unclean energy sources. Further, this study provides strong evidence that clean energy usage through solar energy usage has strong gender based dynamics. This study shows that female members of a household are the worst sufferers of negative impact of unclean energy usage. Solar energy usage can improve gender disparity condition through improving woman health outcomes.

5. Conclusion:

This study shows that clean energy usage by means solar energy usage improves the health status of user households. The findings provide empirical evidence of the effectiveness of solar energy usage as a clean energy to reduce negative impact of using unclean energy sources like kerosene. Energy policy makers need to focus on how to improve the clean energy usage like solar energy usage to reduce unclean energy usage. Further, this study suggests that public health policy makers need to coordinate with energy policy makers to address the health issues related to unclean energy usage, ensuring access to sustainable and affordable energy for all, the SDG-7. Further, renewable energy sources like solar energy, wind energy, biogas need to be promoted so that unclean energy usage reduces as it affects public health significantly. Governments should formulate energy policy in such a way that renewable energy sources like solar energy, wind energy, biogas became affordable to the mass people. Further, livelihood programs, cash transfer programs and

information session should be arranged to make alternative energy sources affordable and demanding at micro level. Promotion of solar energy usage can empower women through improving their health condition.

The limitations of the study need to be considered during interpreting the findings of the study. The study examines only local average treatment effect of the compliers in place of average treatment effect because of instrumental variable setting. Then the study use only a binary variable whether the household use solar energy usage as the treatment variable but the amount of usage could have been a better treatment. Finally, the mediating factor like reduction in unclean energy is assumed as a major reason of improved health but no empirical proof can be established under the present study. Future research needs to focus on exploring the impact of actual usage of clean energy on health outcomes and the mediating factor like reduction in usage of unclean energy sources need to be examined.

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Figure 1: The study Area