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The prospects of decentralised solar energy home systems in rural communities: User experience, determinants, and impact of free solar power on the energy poverty cycle

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ABSTRACT

Distributed solar photovoltaic is a well-established technology to meet small-scale rural energy needs in an affordable, reliable, and carbon-neutral manner. Such socio-technical transitions offer substantive support to address energy poverty and act as a key tool to realise human well-being, economic prosperity, and environmental conservation envisioned under Sustainable development goals (SDGs). In this study, households using solar photovoltaic were surveyed to determine prospects of solar energy use in rural communities. The participants include rural households from Uttar Pradesh, India that had received i) a small scale and subsidised solar systems, ii) obtained paid connection from solar micrograms, and iii) those who purchased solar systems for power reliability. We report high satisfaction with distributed solar photovoltaic among rural households. The factors influencing a desire to procure additional solar power include income, level of education, duration of solar use, user satisfaction, time of day for the power supply and financial support for procurement. Our findings also suggest that freely given solar power offers limited incentives for procuring more solar power. We further analyse the policy of welfare using energy justice as a conceptual tool. This can explain paradoxical aspects of subsidies that are widely used as a socio-political tool to improve quality of life for those that are disadvantaged but fail to address fundamental structural aspects of the energy system that are underscored by procedural justice issues. We propose policies for distributed clean energy in emerging countries must address concurrent energy transitions and energy justice frameworks to support sustained decentralised solar transitions. Without these two foundations operating in tandem, carbon lock-in and the energy poverty cycle will be inexorably linked.

1. Introduction

The global community has recognised electricity access is the first footstep and a precondition for socio-economic progress. Yet, about 1 billion people across the globe lack access to electricity that limits people's opportunities to achieve a better quality of life [1]. The majority of this population is poor and live in rural areas where the cost of grid extension is high. In recognition of the energy inequality around the world, the United Nations Sustainable Development Goal (SDG) 7 seeks to provide affordable, reliable and clean energy underpinned by a focus on universal access by 2030. The success of SDG#7 lies in sustainable energy transitions which is characterised by its multi-scalar nature [2] and comprise of two related, yet diverse elements, namely socio-technical systems that deals with integration of technology and innovation with society (supply-side factors), and energy justice which is framed around cost and risk of energy production and distribution (demand-side factors) [3]. SDG#7 uniquely brings complementarity of both socio-technical systems and social justice to promote sustainable energy for all. In the pursuit of addressing energy poverty, there are interwoven themes linking production and consumption of energy as well as its distribution and procedures [4]. To this end, technology becomes critical for achieving environmental sustainability in terms of production and consumption to break the carbon lock-in. To this, it is equally critical to consider energy justice aspects given the high population stuck within the energy poverty cycle due to a lack of access to, and affordability of modern energy services. It is these interwoven technical and social aspects that contribute to and reinforce the current disproportionate and uneven distribution of energy. For many, it is the

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failure of distributive justice principles within the energy sector that serves as an impenetrable barrier just as carbon lock-in reinforces traditional energy generation and distribution systems. Combined, there exists both inter and intra-generational disadvantage and exclusion of a right to energy and a clean environment perpetuating the socio, economic and environmental conditions that are linked to and reinforce the energy poverty cycle [5].

Under SDGs, the uptake of decentralised solar has advanced access to electricity across various developing countries and contributed to a 10% decline in global deficit in electricity access in the last 15 years [6]. In particular, India commissioned rural electrification programs [7,8] to achieve universal access and National Action Plan on Climate Change (NAPCC) that aims 40% electricity generation from non-fossil fuel-based sources by 2030 [9,10] to support agenda of supplying cleaner power with climate remediation. These efforts present a unique facet of rural electrification in India where a national grid network connects all census villages and over 99% of households across the country [11,12] yet a large population especially rural communities remain electricity-deprived due to poor power reliability [13,14]. This represents an energy justice distribution and procedural paradox reflecting a dependency on traditional centralised and carbon-based energy that at a high level has 'achieved' its distribution goals yet fails to fully comprehend the nuanced complexities of the socio-economic, technological and geographic variances affecting energy needs across the country [15]. What is observed in India is that a centralised grid due to its unreliability does not consistently offer the expected economic (e.g. support income-generating rural microbusinesses) or lifestyle gains (e.g. convenience of working in light with use of fan/heater while performing household chores after sunset and infotainment), nor has it resolved the geographical inequity of power distribution. Procedurally these failings are compounded by the highly variable 'quality' of rural electricity infrastructure. Four factors can define quality in this case: power supply that is not reliable during peak hours and that varies across locations; maintenance of the infrastructure that is compromised due to financial challenges of the distribution companies [16]; the high transmission losses within the grid; and low revenue generation in part reflecting the limited capacity for many residents to pay [17,18].

Unreliable and highly subsidised electricity supply in rural areas presents a vicious cycle where frequent outages and poor earnings lead to lower revenues [13], and lower revenues deter distribution companies to invest in rural infrastructure. Universal access to energy to many parts of rural India is economically unviable despite the rapidly growing population in these regions and the current government led the electrification program [19]. India, therefore, is faced with a compelling need to modernise its electricity sector to disrupt and break the existing carbon lock-in and to strengthen governance systems to support energy justice principles and the sustainable and equitable economic growth [16,20,21].

From a socio-technical perspective, decentralised solar power generation is increasingly employed as a viable alternative to address existing challenges in rural electrification [22]. Globally, decentralised electrification using solar photovoltaic applications is steadily employed by governments and entrepreneurs to deploy electricity services to rural and remote communities in a cost-effective manner [23]. Regionally, solar photovoltaics (PV) is one of the most commonly used technologies for decentralised rural electrification in South Asia, yet there are fewer projects that have achieved commercial success [24,25].

India has a long history of off-grid solar application deployment that stemmed from the oil crisis in the 1970s. Over the past four decades, it has used various mechanisms ranging from early demonstration projects, philanthropic initiatives, subsidy [26] and public grants based programs and market-based mechanisms including retail and Pay-As-You-Go (PAYG)[1] based installations to disseminate solar PV products [27–29]. However, systematic and significant development of this sector only started in 2009 [30] with the announcement of the national solar program followed by increasing private sector investment and innovations [31]. Key programmes supporting off-grid solar summarised in Table 1, represents major initiatives of the national government that are implemented through national or state nodal agencies, commercial banks, and private suppliers. However, the effectiveness of these initiatives have not fully address the multifaceted challenges including distribution and procedural energy justice issues [5,32] that range from how to successfully negotiate and deliver partnerships between public and private actors and how to provide the required capital, operational efficiencies and new business practices to drive solar PV based energy transition [33].

Researchers have suggested that grid expansion alone would not be adequate to provide universal energy access and reliable supply in India, rather the grid will be necessary to complement existing infrastructure with standalone and local community level off-grid supply [25,34]. Off-grid energy systems are increasingly becoming competitive to main grid distribution [35–37] due to the falling price of solar technology and evolving business innovations [38,39]. However, the emerging financial and product innovation has not been able to scale-up and overcome an inherent path resistance to decentralised solar energy [31,40]. This is in spite of both national and state governments having policies and public programs to promote decentralised solar development [41–44]. As observed in previous studies, some of the path limiting factors in the adoption of decentralised solar in rural areas include: high cost; lack of financial support; limited awareness; poor consumer engagement; poor quality services; and lack of targeted approach to serve rural poor [29,

Table 1
Key initiative for promoting off-grid solar for rural residential use. Source:; [7,8].

Initiative	Summary description	Duration
Saubhagya Scheme	A national program to provide electricity to all households with a provision to use off-grid solar installation.	2017 onwards
Jawaharlal Nehru National Solar Mission (JNNSM)	The target of installing 2000 MW off-grid solar PV systems by 2022. Capital subsidies and incentives for solar lamps, solar home systems, and installation of solar mini/microgrids in rural and remote areas.	2010 onwards
Decentralised Distributed Generation (DDG)	The scheme under Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY)/Deendayal Upadhyaya Gram Jyoti Yojana (DDUGJY) to electrify un-electrified villages, where the grid cannot be extended, through mini-grids. This also included villages that receive less than 6 h of electricity per day.	2009–2018
Remote Village Electrification Programme	Subsidised renewables for electrification of remote un-electrified census villages and un-electrified hamlets (of electrified census villages) where grid-extension is either not cost-effective or not feasible.	2001–2005
AkshayUrja programme	Creation of a network of a solar retail outlet in each district across India.	1995 onwards

[1] For details on PAYG refer, Yadav, P., Heynen, A.P., Palit, D., 2019. Pay-As-You-Go financing: A model for viable and widespread deployment of solar home systems in rural India. Energy for Sustainable Development 48, 139–153.

45–47]. Such issues and the nexus between electricity and rural/regional development are well recognised at the macro-economic level. Yet the relationship between electricity and development, especially to support decentralised technologies and how they can address the energy poverty cycle at the local level, is not fully characterised. Therefore, this study attempts to bring empirical insights drawing from interviews with rural communities to offer commentary and direction to the complex nature of socio-technical and energy justice transitions.

2. Context of the household survey

To gain deep understanding of current and future household energy options it is necessary to consider traditional, technical, and economic drivers such as willingness and capacity to pay, convenience, and product experience if lasting energy solutions for the rural communities are to be realised [48,49]. Combined, household-level data can provide the granular insights that can assist policymakers to understand geographical, demographic and socio-economic conditions which can be otherwise averaged out through national or state-level datasets. Such data are few and far between, and by way of example, there is no public database of decentralised solar users (households) in the state of Uttar Pradesh. To fill this gap, this study undertook a randomised selection of households across 7 districts in the state of Uttar Pradesh (UP) as representative of the decentralised solar PV users in the state. The 249 surveyed households were grouped into two categories: those having only solar PV users (G-O+) (105 households) and those with both solar PV and main grid (G + O+) (144 households). The majority of households used solar power for residential use only. A smaller subset of these households also used their power for small business activities (e.g. vegetable hawkers, general (condiment) stores, repair shops, etc.). Within sampled households, four different types of decentralised solar technologies were used (as shown in "Solar technology" in Table 2) with usage between 10 W and 40 W. This power demand represented Tier 1 or 2 level electricity services as per the multi-tier framework [23] for power needs met through solar power. Therefore, data from different technology users have been used in the analysis despite these technologies offer a different level of service. Table 2 provides details of solar users in surveyed households.

The primary research aim of the study was to explore the effect of distributing free solar power to households and their subsequent intention to obtain more solar power. In this study, 27% sampled households received either free solar home system or a free connection from a solar microgrid which allows us to evaluate the role of freely given solar power on the creating more demand for reliable power. The study also aimed to evaluate the experience of rural households using solar PV systems. We present findings under the following research questions:

- Are rural households satisfied using decentralised solar power?
- How does household income, level of education, duration of solar use and hours of power supply determine the desire for acquiring more solar power?
- Does freely given solar power support an ongoing desire for increased solar use?

The findings and interpreted potential recommendations are summarised in the result and discussion section.

Table 2
Description of decentralised solar PV use in households.

Responses (N = 249)	Frequency	Percentage
Type of households based on the source of electricity[a]		
G + O+ (solar and grid user)	144	57.8
G-O+ (only solar user)	105	42.1
Solar technology		
Solar lamp (lantern)	49	19.6
Solar Power Pack (up to 40 W)	66	26.5
Solar PV System (40 W and above)	20	8
Solar microgrid connection	114	45.7
Duration of solar use		
0 year–1 year	63	25.3
1 year–3 year	71	28.5
3 year–5 year	69	27.7
Over 5 year	46	18.4
Hours of electricity per day		
Up to 4 h	42	16.8
Over 4 h	207	83.1
Mode of procurement		
Received a free SHS/free solar electricity connection as part of the government program	65	26.1
Purchased SHS and received a government subsidy	1	0.4
Pay monthly bill for solar connection or purchased standalone SHS on a monthly instalment	132	53
Purchased SHS by paying the full cost upfront	51	20.4

[a] The solar lantern users had stopped using solar power at the time of survey either due to the non-functioning battery or other technical issues or discontinued using solar power after the arrival of the main grid in the village.

3. Materials and method

3.1. Study area and data acquisition

The survey was conducted in seven districts of northern State of Uttar Pradesh in India (Fig. 1). The villages were selected based on secondary information on the location of existing off-grid solar installations. A thorough search of public and private enterprises' websites was performed to identify specific villages with households were using off-grid solar applications (solar lantern, solar home system, and mini/microgrid). This was further complemented by local information sources including discussions with state and district utility personnel to ensure the accuracy of village location. Households within the seven districts that used solar PV applications installed by the government under various programs[2] [50,51] or had power connection from a solar mini/microgrid run by private entrepreneurs were randomly shortlisted for the survey. Upon arrival at the survey location, households using solar power were contacted for an interview with the help of either the village head or state utility local official/contractor/local member of the public (or a combination these) with good knowledge of the village. The questionnaire[3] was designed in English then translated in Hindi (official and commonly understood the language in the state). Research Ethics Committee approval was obtained prior to conducting the household surveys. 249 surveys were undertaken from April 2016 to June 2016 in person at the participant's house. The purpose of the study was explained in Hindi and informed consent was signed by interested households before starting the interview. The interviews lasted from 30 to 45 min. The questionnaire was comprised of closed-ended qualitative and quantitative questions with provision to capture elaborated responses, where applicable. For existing solar users, questions including information about demographics and current use of solar power were asked. Households were also asked for their views on the use of solar power in the future. Participants answered most questions (independently or with support from a family member) and inaccurate or incomplete data were omitted from analysis to avoid skewed results. The survey questionnaire collected a combination of quantitative and qualitative information. The qualitative dataset was transformed into numerical data to use variables in the statistical model [52].

[2] For example, some villages were chosen from UPNEDA website listed under beneficiary of Dr. Ram Manohar Lohia Samagra Gram Vikas Yojana and Janeshwar Mishra Yojna two flagship programs run by the Uttar Pradesh government from 2012 to 2017.

[3] Refer Appendix A for list of survey questions used in this paper.

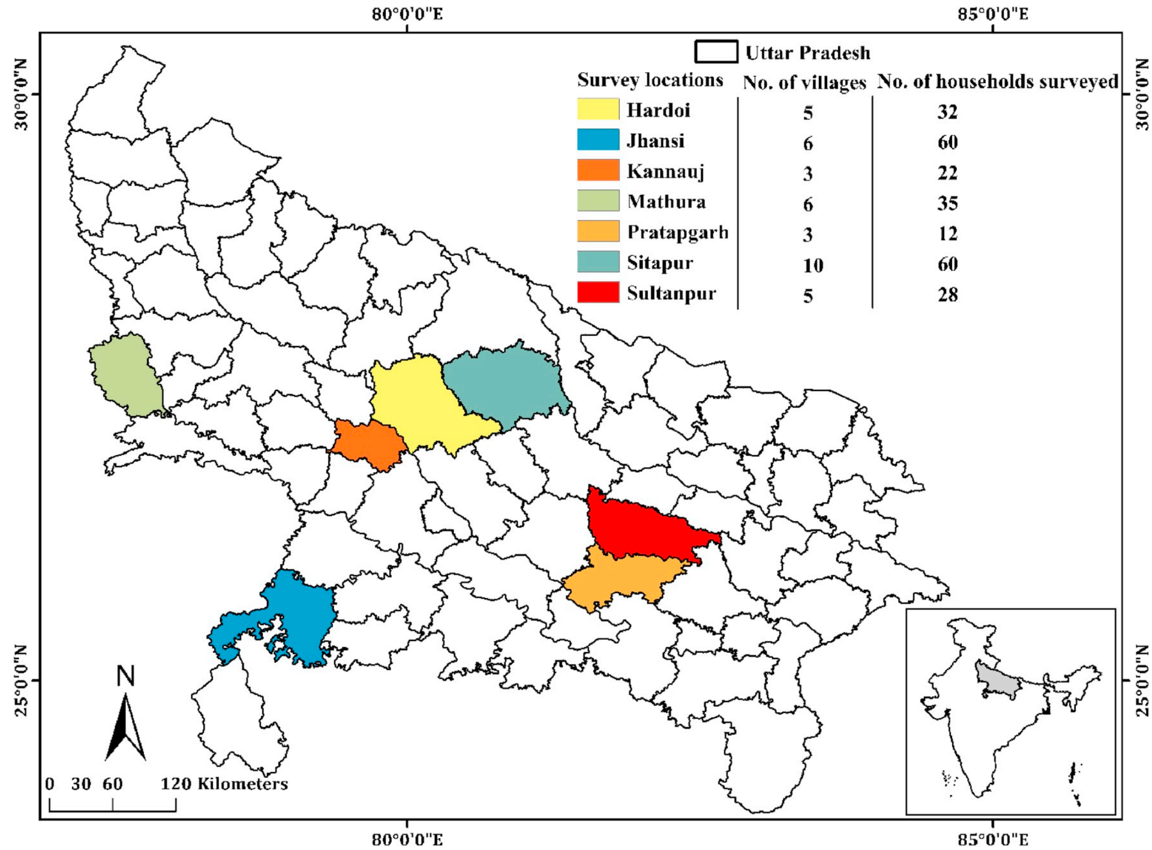

Fig. 1. Summary of the field survey conducted in Uttar Pradesh.

3.2. Statistical framework

The primary focus of this study is to understand the sustainability of solar PV power. We highlight this in the form of households' consideration to source more power showing the continuity of solar use. The inclination of households to desire for more solar power can have three possibilities from their existing usage i.e. positive (households desire more energy), neutral/uncertain, and negative (no desire for more energy). Therefore, we conducted a multinomial probit regression for estimating these possibilities. Importantly, since our response variable is categorical in nature with outcomes that have no natural ordering, the multinomial probit is used to fit the model.

For brevity, the estimated multinomial probit regression model can be expressed as [53]:

$$z_i = R_i\beta + u_{i,} \qquad u_i \sim N(0, V), . \tag{1}$$

$$y_{i,j} = 1, \quad if \quad z_{i,j} \geq \max(z_i), . \tag{2}$$

$= \quad otherwise$

Where, R_i is a $p \times k$ matrix of the values of the independent variables for the i th observation for each alternative; N is the independent observations on multinomial vector y_i, p denotes alternative choices with a $z_i(p \times 1)$ as the latent normal vector of each choice selection; j choice alternative observed if j th component of z_i appears larger than the entire components, β denotes the parameter estimates, V represents the sample size, and u_i denotes the white noise assumed to be independent, standard normal and random variables. To test the validity of the estimated probit models for unbiased statistical inferences, the study examined the marginal effects of the independent variables, with corresponding plots provided in Appendix B.

4. Results and discussion

4.1. Experience of rural households with decentralised solar PV use

Table 3 provides a level of satisfaction reported by the participants in comparison to previous power source used in the households. A high level of satisfaction was recorded among rural solar users. User satisfaction was remarkably high in households using solar only (G-O+). For this group over 30% participants (as compared to 21% of G+O+ households) rated solar power better than previously used lighting sources, in this case, low-quality lighting sources (kerosene or candles).

The level of satisfaction was tested in relation to six variables safety, overall performance, battery life, product quality, maintenance support, and power availability (Fig. 2 and Fig. 3). Households reported high satisfaction across all six aspects, although less in some households with respect to maintenance. Satisfaction comparing household types (G+O+ and G-O+) also showed similar trends (Fig. 3) with households using only solar reported being more satisfied than those using solar in addition to the grid. These findings indicate that positive user experience in rural areas certainly offer opportunities for businesses to engage with

Table 3
Households' satisfaction level with the use of solar PV as compared to a previous power source.

Satisfaction	Overall (249)		G + O+ (144)		G-O+ (105)	
	Frequency	%	Frequency	%	Frequency	%
Below expectation	25	10.0	22	8.8	3	1.2
As good as previous source	90	36.1	70	28.1	20	8.0
Much better	134	53.9	52	20.9	82	33

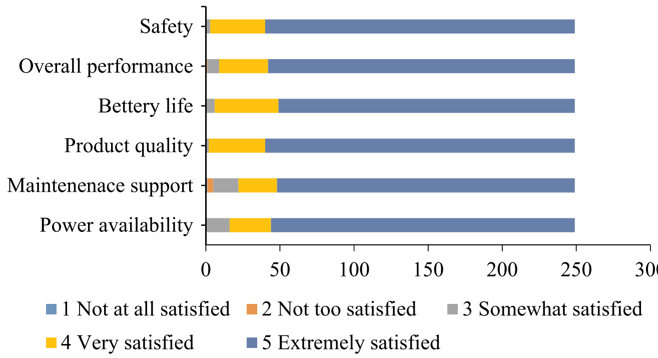

Fig. 2. Overall household satisfaction in solar PV users.

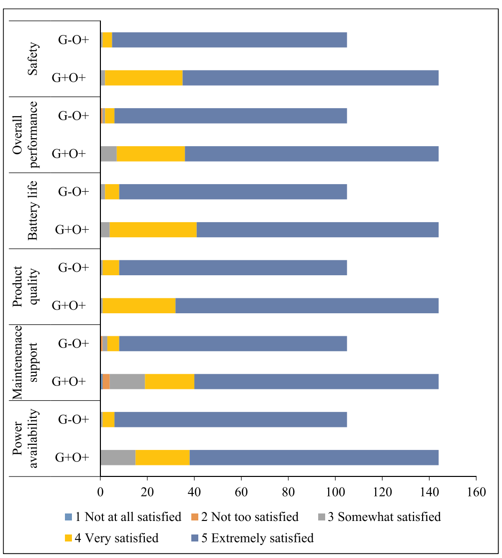

Fig. 3. User satisfaction by household types.

rural households to address unmet energy demand and further grow the market.

We also predicted the role of overall users' satisfaction with solar on the likelihood of households to the desire for solar power (Table 4). We found that satisfied households were likely to desire for more solar power. In other words, 1% change in households' satisfaction increases the desire for solar by 0.16%.

This suggests policies supporting high-quality products and services are more likely to support ongoing decentralised solar adoption. This includes appropriate assessment of energy consumption of prospective consumer and installation of suitably sized solar home system or solar energy supply, effective user training, periodic system maintenance, provision to charge a small fee on an ongoing basis to ensure low burden on household for battery replacement. Similarly, it also points to the solar businesses to keep customer satisfaction as a key indicator in their business strategy for creating long-term partnerships with customers, hence, help to increase the share of renewable energy in the energy portfolio. In summary, lowering cost and achieving higher user experience are key to support the sustainable transition in rural areas.

Table 4
Random effects multinomial probit estimates of households' satisfaction with solar use (4.a) and corresponding marginal effects (4.b).

Desire for solar power	Coeff.	Std. Err.
Part 4.a. Random effects		
No	−0.161	0.186
Yes	0.585***	0.190
Part 4.b. Marginal effects		
User rating on solar use	dy/dx	Std. Err.
No	−0.092**	0.038
Maybe	−0.070	0.046
Yes	0.162***	0.041

Note: Response "May be" is base outcome, ***$p < 0.001$, **$p < 0.05$, *$p < 0.1$.

4.2. Factors influencing sustained solar adoption in rural households

The survey contained questions about demographic data of respondent (gender, and level of education) and household (family size, studying members, type of dwelling and income) to ascertain their background in relation to electricity needs. Table 5 shows the summary statistics of households using solar PV that participated in the survey.

Further to the high satisfaction reported in the previous section, this study attempted to investigate how demographic factors, along with the duration of solar use and solar power supply, determined households' desire for more solar power or higher configurations of solar PV technologies.

Using a multinomial probit regression model, we estimated the effect of these determinants independently, and their combined effect in predicting the likelihood of households' desire for solar power. First, we present coefficients from the output of a probit regression in Table 6.

Table 5
Descriptive statistics for participating households.

Description	Frequency (N = 249)	Percent (%)	Mean	SD
Relationship of participants to household head				
Household head	211	84.74		
Son/Daughter	15	6.02		
Spouse	23	0.24		
Gender				
Female	22	8.84	1.09	0.28
Male	227	91.16		
Age				
18–24	7	2.81	41.53	10.96
25–44	155	62.25		
45–64	81	32.53		
65–79	6	2.41		
Level of education				
Never attended school	71	28.51	2.88	1.71
Up to class 5	53	21.29		
Up to class 8	42	16.87		
Up to class 12	55	22.09		
Bachelor's degree and above	28	11.24		
Household size				
1–3	3	1.20	6.63	2.03
4–6	131	52.61		
7–9	92	36.95		
10 and more	23	9.24		
Members studying				
1	64	25.70	1.80	1.05
2	105	42.17		
3	41	16.47		
4	8	3.21		
5 or above	4	1.61		
None	27	10.84		
Dwelling type				
Stable (house made up of bricks and cement)	77	30.92		
Semi-Stable (mixed-bricks and timber & mud)	134	53.82		
Kachha (mud-house)	24	9.64		
Unstable (cartons, biomass)	14	5.62		
Average annual income (INR)				
1000 - 33,000	171	68.67	38850	43619
33,001–55,000	30	12.05		
55,001–88,800	19	7.63		
88,801–1,50,000	13	5.22		
1,50,000 and above	14	5.62		
Prefer not to answer	2	0.80		

Table 6
Multinomial probit regression.

Desire for more solar power		Coef.	SE
a. Estimates of household desire for solar power using demographic determinants independently			
Annual income	No	−0.215	0.129
	Yes	0.253**	0.101
Type of households based on source of electricity (Household type)	No	−0.498*	0.257
	Yes	0.106	0.242
Participant's education level	No	−0.147	0.094
	Yes	0.240***	0.088
Household size	No	−0.373*	0.193
	Yes	−0.132	0.175
Members studying in households (Members studying)	No	−0.121	0.124
	Yes	0.209*	0.116
Dwelling type	No	0.651***	0.178
	Yes	0.318**	0.155
Duration of solar use (years)	No	−0.733***	0.137
	Yes	0.208*	0.121
Hours of electricity from solar per day (Reliability of solar)	No	−0.949***	0.323
	Yes	−0.301	0.338
Mode of procuring solar PV (Solar procurement)	No	−0.973***	0.137
	Yes	0.440***	0.141

b. Estimates of household desire for solar power using components of solar use and solar procurement determinants independently				
Duration of solar use	No	*1 to 3 years*	−1.745***	0.359
		3 to 5 years	−1.932***	0.348
		Over 5 years	−1.820***	0.460
	Yes	*1 to 3 years*	0.737*	0.391
		3 to 5 years	−0.318	0.412
		Over 5 years	1.321***	0.423
Note: 0 to1 year (base outcome).				
Solar procurement	No	*with subsidy*	−1.707	6469078
		in instalment	−2.818***	0.330
		upfront payment	−1.843***	0.675
	Yes	*with subsidy*	10.866	1718655
		in instalment	−1.470***	0.368
		upfront payment	2.244***	0.500
Note: Solar procurement - free (base outcome)				

c. Estimates of household desire for solar power using the combined effect of solar use determinants and income		
No		
Annual income	0.201	0.156
Solar procurement	−1.614***	0.281
Reliability of solar	1.365***	0.513
Duration of solar use	0.066	0.216
User rating on solar use	0.370	0.255
Yes		
Annual income	0.238	0.114
Solar procurement	0.960***	0.231
Reliability of solar	−2.377***	0.527
Duration of solar use	0.018	0.164
User rating on solar use	0.475**	0.207

Note: Maybe is base outcome, ***p < 0.001, **p < 0.05,*p < 0.1.

We interpret the marginal effects (Table 7) to estimate the probability of the outcome (dependent) variable with respect to predictor variables, holding all other predictors constant at the same values. Respondents were asked to choose three possibilities in the forms of i) no, ii) may be/uncertain, and iii) yes that were presented by the outcome variable (desire to procure more solar power). Table 7 summarises several factors that affect a household's consideration to procuring more solar power. On estimating for individual determinants independently, we found that annual income, level of education, members studying in the household, duration of solar use and mode of procurement significantly affected the desire to procure more solar power in households using off-grid solar technologies in rural Uttar Pradesh. Factors including use of solar technologies with or without a grid, household size, dwelling type and duration of electricity provided by solar technology had no significant effect on consideration of procuring bigger systems or subscribing more solar power. Interestingly, over 80% of

Table 7
Marginal effect (computed from Table 6 a, b and c).

	dy/dx	Std. Err.
a: Marginal effects for determinants when analysed independently		
Annual income		
No	−0.074***	0.027
Maybe	−0.010	0.028
Yes	0.083***	0.022
Household type		
No	−0.129	0.054
Maybe	0.053	0.063
yes	0.076	0.057
Participant's education level		
No	−0.056***	0.019
Maybe	−0.017	0.023
Yes	0.0734***	0.018
HH size		
No	−0.077*	0.042
Maybe	0.074	0.046
Yes	0.003	0.042
Members studying		
No	−0.049*	0.026
Maybe	−0.017	0.030
Yes	0.066*	0.026
Dwelling type		
No	0.120***	0.036
Maybe	−0.138***	0.038
Yes	0.018	0.036
Duration of solar use		
No	−0.164***	0.021
Maybe	0.059	0.028
Yes	0.105***	0.023
Reliability of solar		
No	−0.194***	0.063
Maybe	0.180	0.083
Yes	0.014	0.077
Solar procurement		
No	−0.172***	0.011
Maybe	0.027	0.027
Yes	0.145***	0.025
b: Marginal effects for solar power using components of solar use and solar procurement determinants independently		
Duration of solar use	*0 to 1 year* **is** base outcome	
1 to 3 years		
No	−0.522***	0.071
Maybe	0.193	0.082
Yes	0.329***	0.068
3 to 5 years		
No	−0.490***	0.074
Maybe	0.410***	0.079
Yes	0.080	0.056
Over 5 years		
No	−0.570***	0.071
Maybe	0.062	0.090
Yes	0.508***	0.080
Solar procurement	*free is base outcome*	
with subsidy		
No	−0.708***	0.056
Maybe	−0.154***	0.045
Yes	0.862	0.668
in instalment		
No	−0.602***	0.062
Maybe	0.626***	0.057
Yes	−0.024	0.051
upfront payment		
No	−0.688***	0.060
Maybe	−0.095*	0.056
Yes	0.783***	0.057
c: Estimates using the combined effect of solar use determinants and household income		
Annual income		
No	0.018	0.021
Maybe	−0.056**	0.026
Yes	0.038*	0.020
Solar procurement		

(*continued on next page*)

Table 7 (*continued*)

c: Estimates using the combined effect of solar use determinants and household income		
No	−0.274***	0.032
Maybe	0.014	0.041
Yes	0.260***	0.039
Reliability of solar		
No	0.301***	0.072
Maybe	0.228**	0.094
Yes	−0.529***	0.095
Duration of solar use		
No	0.009	0.030
Maybe	−0.009	0.037
Yes	0.001	0.031
User satisfaction rating on solar use		
No	0.032	0.035
Maybe	−0.110**	0.044
Yes	0.077**	0.038

solar users in the sample received solar electricity for over 4 h per day (Table 2), enabled by electricity stored in their battery. This permitted access to lighting and mobile charging (with occasional use of fan) after sunset for 4 over hours that can be a reason for the duration of power having less significance on households' desire to procure more solar power.

The marginal effects (Table 7a) related to the procurement of more solar power show that one unit change in annual income, level of education, duration of solar use and mode of procurement increased the probability of desire to procure more solar power by 0.08, 0.07, 0.10 and 0.14 respectively (highly significant, $p = 0.000$). Similarly, members studying in the household was also found significant ($p = 0.01$) where a 1-unit change in it increased the probability of desire to procure more solar power by 0.07 i.e. 1% increase in school-going children within a household increases the chances to procure more solar by 7% when all variables are held constant.

Secondly, on realising the significance of duration of solar use, we further examined the specific duration of use at which households are likely to desire for more solar. Solar use duration from 1 to 3 years or over 5 years predicted an increasing desire to use more solar. However, users between 3 and 5 years showed a declining desire. This may present a view that battery performance starts to fail after about 4 years. Based on the comment from one of the households on battery replacement and describing it as a "costly and tedious task" can be one of the reasons for the solar user between 3 and 5 years temporarily not wanting more solar. For the group using solar over 5 years, they reported an optimistic view on solar power that may suggest battery replacement renews their confidence in the technology.

PV battery lifetime and servicing have become problematic to consumers, especially in developing countries. Previous studies also revealed service fee, battery lifetime and maintenance as a limitation to people's willingness to acquire solar PV if there's another alternative [54,55]. This suggests solar businesses should address this concern and should attempt to make the experience of battery replacement and overall maintenance in rural areas a less taxing. This may extend to supporting rural households get their battery replaced with a product of verified quality in order to address scepticism regarding maintenance service and the longevity of off-grid solar, including its various components. However, businesses must also offer an easy payment model for battery replacement to support sustained use of solar in rural communities.

We also found that households that obtained their PV system for free were less inclined to desire more power than those paid for their system in full or those who had received a partial subsidy (Table 7b) to support their purchase. Also notable in this analysis is that households who were paying monthly fee or instalment for their solar system were not inclined to desire for more solar. The majority of households in this group were poor and the nature of their solar system was microgrid that was able to support 2–3 light points and 1 mobile charging point. Some respondents in this group indicated their existing household's expenditure meant that there was no additional capacity to pay.

There is ample literature that suggests household income is one of the critical factors that affect the adoption of solar power [35,49,56]. In this study, we estimated regression (Table 7c) by including all individual determinants related to solar power use along with the income to determine their combined effect. We found a similar effect as identified in individual estimation (Table 7a). The marginal effects show that one-unit change in annual income, mode of procurement, and household satisfaction increases the probability of desire to procure more solar power by 0.04, 0.26, and 0.08 respectively. While one unit changes the reliability of solar power decreases the probability of desire to procure more solar power by 0.53. Therefore, energy transition planning should address both supply reliability along with the above-mentioned demand-side factors (annual income, mode of procurement, and household satisfaction) with a key interest in the identification of appropriate socio-technical needs of the communities and devise suitable strategies and policies.

As noted in this section, the determinants including the level of education, studying members in the household, duration of solar use and mode of procurement influence adoption and usage of decentralised solar PV in rural households. However, we also report the high cost and poor quality of energy services are key deterrents to energy transition in poor communities. From the energy justice viewpoint, the principle of sharing benefits and burden by all does not apply in the context of rural poor communities in low or middle-income countries in its existing notion which is largely build on western philosophy [57]. A proportionate and need-based distribution and effective mechanism to address socio-economic disparity (Fig. 4) in this community should be the cornerstone of any policy or strategy dealing with rural energy transition in developing nations.

Tenets of energy justice (equal rights and fair distribution) certainly do not construe a notion of a conflict with environmental sustainability that aims to reduce consumption (especially in high-income countries). Therefore, the use of the justice principle should be carefully applied in the context of a society that is intended to undergo a clean energy transition. Access to power in rural India or similar communities should be pursued in a phased manner that first focuses on addressing energy poverty and gradually enable these communities to self-finance their energy needs and support transition from subsistence energy use to the ideal level of energy use (in accordance with their need, aspiration, and affordability). In summary, prioritising affordability of decentralised solar system and providing strong customer engagement and service focused business model can shape a more viable solution to rural energy poverty woes.

4.3. Free solar power to rural households and implications for further adoption

4.3.1. Energy justice as an analytical framework

Sustainable development goals bring together the agendas of sustainable energy access and environmental remediation and carbon pollution. These agendas prompt policymakers to leverage social and technical systems yet have to consider deeply engrained energy inequality by way of geographic energy distribution that extend between nations (global north and global south), within nations (urban and rural areas), and through distribution systems (grid-connected and off-grid households). In developing counties, the pathway of energy acquisition and transition to clean energy is further complex and multilayered [57]. This complexity lies in achieving dual goals of universal energy access and low carbon footprints that require a major shift in the socio-technical system. Due to the highly sensitive political nature of these systems, policy dilemmas appear, and contentions will confront policymakers and often block or slow the pace of decision making and thus transition. India presents an appropriate case study where there is

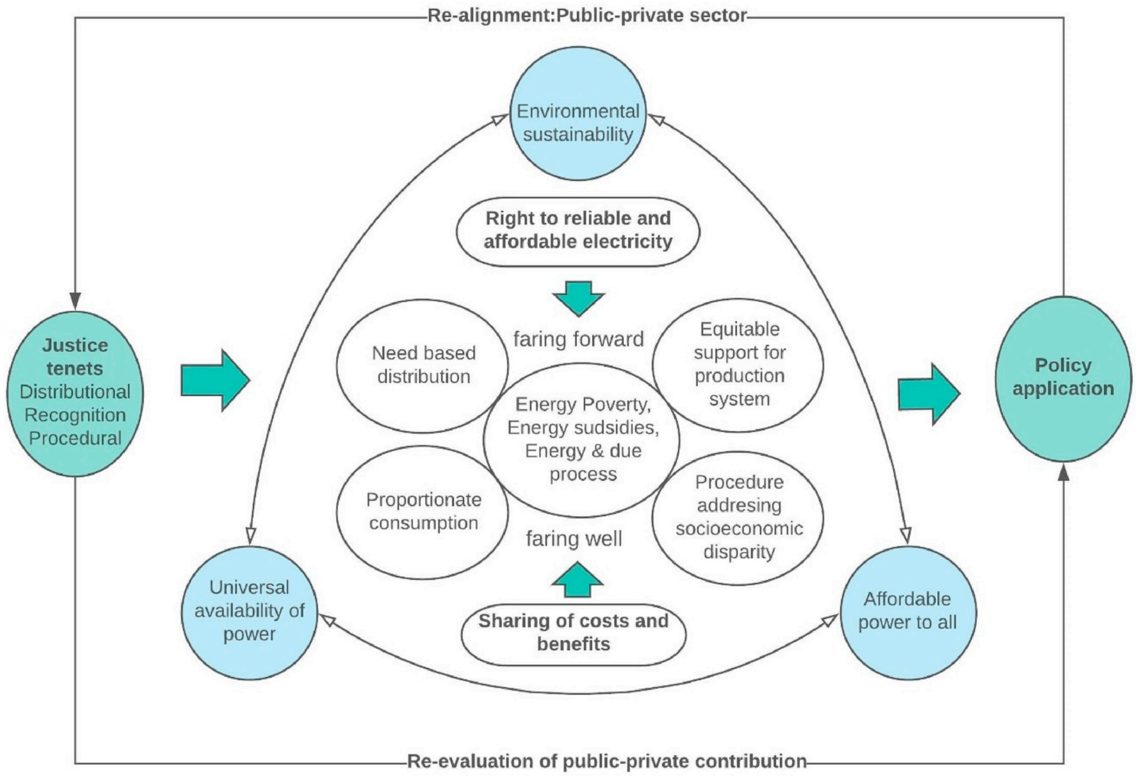

Fig. 4. Conceptualisation of Energy justice framework (Adapted from Refs. [57,59,62]).

deep inequality in energy production and use, along with underlying tensions among various stakeholders, for example, use of preferred technology, cross-subsidisation to support rural electrification and free distribution of solar lighting system to below poverty population that constitute transition complexities [33].

Considering about 25% of solar users in the survey received free or subsidised solar power, this led to a fundamental question of fairness and equality in energy access. Therefore, an energy justice framework (Fig. 4) centred on energy poverty can be applied to understand the impact of household solar photovoltaic (PV) system and their contribution to clean energy transition for rural communities. The energy justice framework discussed in Fig. 4 attempts to suggest a critical role of public-private collaboration to unleash principles of 'faring forward' and 'faring well' in achieving goals of affordable and universal access with environmental conservation.

Justice and ethics are the fundamental prerequisites for a functioning society [58]. Environmental sustainability debates have shaped a new movement in the form of energy justice that has exclusively focused on energy access [5,59]. Energy justice, through its three tenets namely distributional, recognition and procedural, advocates for equitable distribution of benefits and burdens to all [60,61]. As a concept, energy justice has developed into analytical frameworks that are used to investigate broader energy access and policy issues [57,58,60]. This framework is useful to analyse and inform energy decision making by bringing moral and equity aspects that are often missing in energy planning [62] and under-researched in emerging economies [57,63,64]. We consider two dimensions of the energy justice framework that focuses on 1) production and consumption which deals with various energy technologies and how energy is consumed; 2) distribution and procedural, where fair distribution of costs and benefits are viewed under distribution justice while procedural justice ensures the process of decision fair making [32,59]. The growing interest in energy justice conceptual frameworks suggests an emergence of a human-centric approach to policies to identify effective strategies that can address energy inequality. Our framework also brings to light key tensions of electricity distribution and use of subsidies that influence the dissemination of decentralised solar in rural communities. In doing so, it allows unpacking the dynamics of public and private stakeholders in the electricity distribution sector that slow down the pace of clean energy transition in rural areas.

4.3.2. Impact of freely given solar power in Uttar Pradesh

In this subsection, we explicitly present the effect of freely given solar on the desire to procure more solar power (Table 8a) in the surveyed communities. During the survey, over 25% of households (Table 2) reported receiving solar power free of cost under such policy initiatives. This included low-income households that were provided with either free of cost solar home system between 2012 and 2017 and households from 2 villages that were provided with free connections from a solar mini-grid by the state government in Uttar Pradesh.

We found that households who received free solar were either uncertain or expressed no desire for procuring more solar power (Table 8b). This result was anticipated as most of these households were

Table 8
Estimates for freely given solar PV power on the household's desire to procure more and corresponding marginal effect.

Desire for solar power	Coeff.	SE	
a. Random effects multinomial probit estimates			
No			
Free/subsidised solar	2.672***	0.318	
Free/subsidised solar	−0.4574	0.338	
8.b. Marginal effect (computed from Table 8a)			
	dy/dx	Std. Err.	z
No	−0.390***	0.022***	−17.3
Maybe	0.313***	0.059***	5.24
Yes	0.076	0.061	1.27

Note: Maybe is base outcome, ***$p < 0.001$, **$p < 0.05$, *$p < 0.1$.

poor (below the poverty line) and had almost no disposable income to invest in their future electricity needs. Considering the following statement from a respondent, the freely given systems appear a good initiative.

"Being poor, we would have continued using kerosene if the government wouldn't have provided us with the solar. Now, I can light my house in the night, use a fan in the noon and charge a mobile phone when needed."

As these systems age, hastened by a lack of maintenance, many households will be forced to abandon their current step up on the energy ladder. This is arguably due to the fact that fully subsidised programs often run well in the beginning but gradually fail to support the clean energy transition in the absence of effective engagement and post-sales services, observed in Anand and Rao 2016 [65]. The need for ongoing energy assistance beyond the free capital of a system was noted by many respondents:

> "There is no dedicated solar shop where SHS can be fixed. Although, few electric shops do the repair" (mentioned by 7 respondents).

We also found many households were not able to commit to maintaining their systems due to the absence of any effective user training.

> "The person (installer of free 40W SHS under government scheme) didn't tell how to use it" (3 respondents on asking if any user training was provided).

These findings emphasise that maintenance support and consideration of long-term energy future and capacities of poor households are integral to promote sustained benefits of decentralised solar power. We assert that this represents an important and underexplored area of energy justice distribution and procedure. For below poverty line households, policymakers need to consider different approaches. This could include subsidy support but not entirely free, and PAYG (Pay-As-You-Go) model inclusive of maintenance and replacement. This finding supports and enables a proposition that carbon lock-in and energy injustice lock-in can be addressed concurrently [66] and is a needed approach in many developing countries. We contest, however, that new financing arrangements are fundamental.

4.3.3. The energy conundrum

Drawing from the energy justice framework (Fig. 4), alleviation of energy poverty constitutes a conundrum for government in India and other nation states with populations captured within the energy poverty cycle [67,68]. At the macro level, the objectives of access to energy and a clean environment sought by the SDGs present two fundamental challenges under current policy trajectories. First, there is the challenge of energy production to meet current and rising demand but simultaneously having to curb coal-based electricity production for a low carbon energy system. Second, distribution to rural and remote communities under traditional models requires a subsidy for large infrastructure (poles, wire, and centralised generation). Inherent to this approach are geographic constraints and in turn, socio-economic inequalities when compared to the economies of scale, able to achieve when compared to the urban centres. This places government policymakers in a dilemma as to who should they prioritise and whom they should subsidise given their ever-present limited capital. Government and policymakers in deliberating on this issue seem pressed to either pursue a platform of attaining universal energy access under SDG#7 ("faring forward") or promote low carbon technologies for decarbonisation and environmental sustainability ("faring well") [68,69]. Under current distribution and procedural models, this situation presents paradoxical position to either pursue a development agenda which meets needs for the present generation but constitutes an unjust future for posterity that is in carbon lock-in energy system. If a low carbon transition is prioritised, this clearly benefits future generations and the environment but it is seen as expensive and associated with a range of barriers not least energy justice [33]. For India, universal and reliable access is an immediate priority and it can be achieved by opting a balanced and justifiable approach where diverse and appropriate technologies including a mix of grid and off-grid solutions can support a low carbon transition. This must apply the principles of justice in energy if twin goals are to be realised within and between generations.

5. Conclusions

Energy access and environmental sustainability are equally critical to meet sustainable development objectives under SDGs for global peace and prosperity. Clean technologies including solar photovoltaics offer a reliable solution to break the energy poverty cycle without environmental and health consequences. Considering existing political, social and economic realities within developing states around the world, it is important to first achieve equality within policies that recognise traditional centralised systems but do not position these exclusive to emerging off-grid technologies. From an energy transition perspective, there is likely to be the same degree of public subsidy to support businesses to reorient towards a clean and reliable energy paradigm that is underpinned by environmental sustainability. In parallel, new approaches must be cognisant to social justice principles to ensure household energy decisions have a legacy beyond the initial capital investment.

The household data from this study offers new insights into the use of off-grid solar as it reveals determinants to support energy usage and sheds light on the longer-term efficacy of freely given solar technologies. We identify the income, level of education and members studying in the household positively related to the desire for more solar. This finding is consistent and validates the findings in the existing literature. Being unique in studying solar using rural households, the study also sheds light on key factors associated with solar services that are critical to promoting and sustaining their use in rural areas. Customer satisfaction and use of solar home system positively affect the continued or additional use of solar power. Surprisingly, the existing availability of solar power in the household has no effect on a household's desire for more power. This may be because solar technologies are providing a reliable supply for intending hours and households' expectations are already met. Finally, households that have received solar home system free of cost are less inclined to procure or want more solar power suggesting the progression up energy ladder is not linear or path determined. We suggest their lack of interest in obtaining more solar is either due to a lack of income, affordability or that their needs are met with the present solar PV system. The implication of this finding is that households below or near the poverty line may step backward on the energy ladder once their initial solar PV system approaches its useful life. For this reason, alternative distribution policies and models such as Pay As You Go with embedded social support systems and maintenance requirements may offer better carbon and energy justice transition opportunities for rural and remote communities than simply the provision of free energy solutions. This is critical when coupled with a life cycle approach to distributed energy infrastructure and the capacity for households, particularly the poor, to pay for the replacement of and have realistic aspirations for more power.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

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Appendix A. Information collected from respondents during the survey (list of questions used in this paper)

1. Relationship to household head?
2. What is your gender?
3. What is your age?
4. What is the highest level of education you have completed?
5. How many people currently live in your household?
6. How many members in the household are currently studying?
7. The house you live in is?
8. What is your approximate average household annual income?
9. Which solar technology/service are you currently using?
10. For how long you are using this solar technology/service?
11. How many hours of electricity (e.g. Lighting) per day do you get from your solar home system/service?
12. How did you initially get this solar technology installed or avail this service?
13. Please rate your satisfaction with your solar technology/service for following?
14. How would you rate your solar power service as compared to grid electricity or power source you used previously (or your experience of using solar and any other simultaneous power sources like grid/wind/biogas etc.)?
15. Would you consider purchasing a bigger solar power panel or subscribe more energy allowing you to use other home appliances?

Appendix B. Statistical Analysis

4.2: Determinant of sustaining solar adoption in rural households

Following is a list of the corresponding plots for marginal effects of the independent variables discussed in Section 4.2 (summarised in Table 7) and Section 4.3 (Table 8b) in the manuscript. The marginal plots fall within the 95% confidence interval (red vertical line), validating the stability and robustness of the estimated models.

(a)

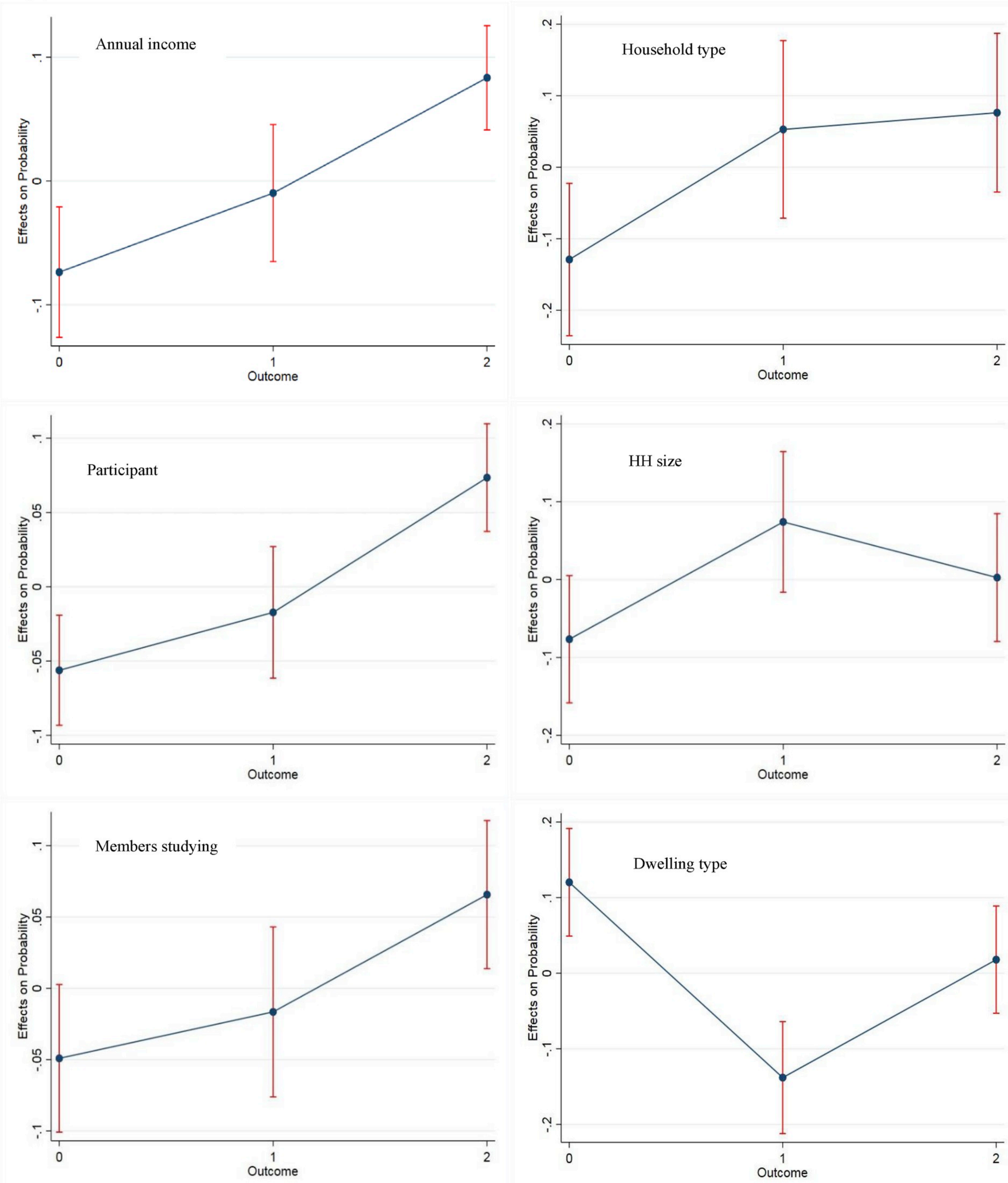

Fig. B1. (a and b): Average marginal effects with 95% CIs.

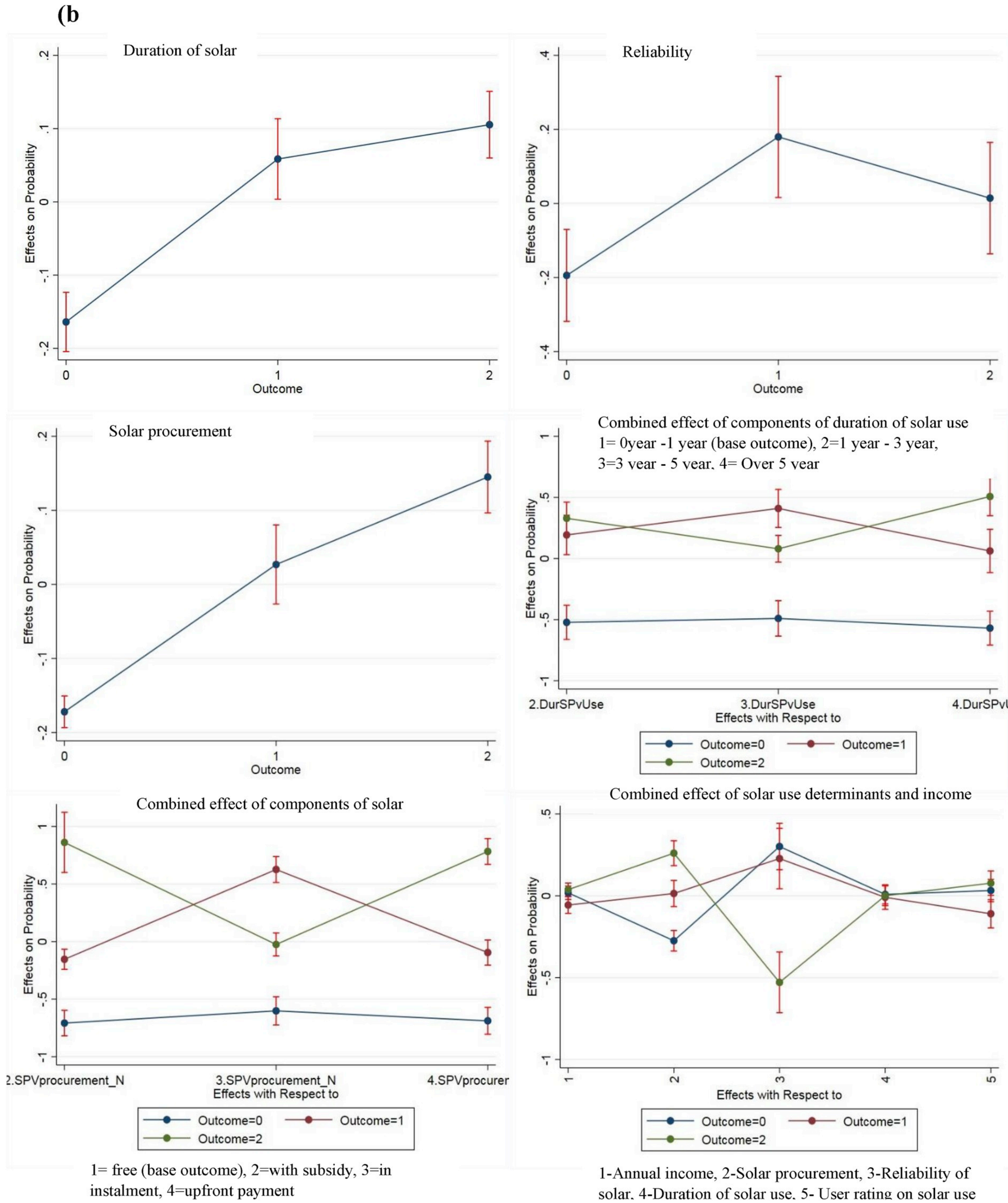

Fig. B1. (*continued*).

4.3: Free solar power to rural households and implications for further adoption

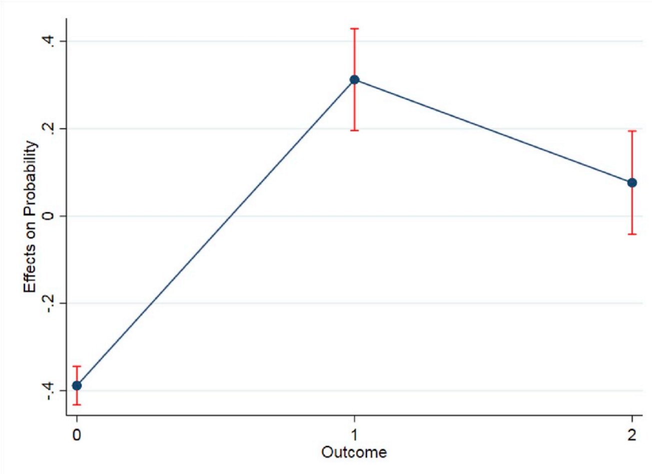

Fig. B2. Average marginal effects of free subsidised solar with 95% CIs.

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