RESEARCH ARTICLE

A Shift to Solar Irrigation Pump-Sets: A Case Study from Uttar Pradesh, India

Juhi Chatterjee* and Tejal Kanitkar†

Abstract: Renewable energy technologies are being actively encouraged in India by policies that promote public and private investment in renewable energy. New regulatory and financial incentives to establish the use of renewable energy, especially in irrigation, have created the potential for a shift towards renewable sources in the sector. This paper analyses the differential nature of the impact and dynamics involved in shifting to solar pump-sets in two villages in Hardoi district, Uttar Pradesh, India. The short-term impact of a private solar mini-grid intervention is evaluated using a pre- and post-intervention evaluation of beneficiaries and non-beneficiaries across different socio-economic classes. The paper offers a comparative analysis of the irrigation costs associated with various fuels, alongside a comparison of annualised lifecycle cost (ALCC) across varying technological and regulatory configurations, demonstrating that energy-efficient electric pump-sets might still be cheaper than all configurations of solar energy. The study found that grid-connected solar pumps are only viable when operated for less than 500 hours annually, while off-grid solar pumps are more cost-effective at higher usage levels. The paper also outlines a framework for the implementation of a hypothetical scheme aimed at promoting solar irrigation among farmers with landholdings exceeding 6 acres. It provides estimates of the potential district-wide costs associated with such a scheme's implementation and finds that implementing a shift to solar for farmers operating on less than 4 acres of land is economically unviable, since grid-based electricity is the least-cost option with respect to irrigation for this group at present. This study thus argues for designing schemes for the promotion of solar technologies that target beneficiaries based on the size of land holdings.

Keywords: Renewable energy, solar irrigation, solar pump-sets, impact evaluation, irrigation, subsidies, policy, Uttar Pradesh, India.

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* PhD Scholar, School of Habitat Studies, Tata Institute of Social Sciences, Mumbai, juhichatterjee18@gmail.com
† Associate Professor, National Institute of Advanced Studies (NIAS), Bengaluru, tejalk@nias.res.in

Introduction

Renewable energy technologies are being actively encouraged in India by policies that promote public and private investment in renewable energy. New regulatory and financial incentives to establish the use of renewable energy, especially in irrigation, have created the potential for a shift towards renewable sources in the sector. The installed capacity of grid-connected and off-grid renewable energy has increased rapidly in recent years across the country. India ranks fourth in the world in renewable energy deployment, with the grid-connected renewable energy capacity increasing from 2.6 GW in March 2014 to 84 GW in May 2024 (Ministry of New and Renewable Energy [MNRE] 2024). In the agricultural sector, too, government is facilitating a shift towards the use of renewable energy sources, especially for irrigation, in order to improve agricultural productivity while minimising ecological harm.

While the viability of renewable energy sources is still contested on account of high installation costs, questions of energy security and environmental effects are driving a shift from diesel and electric pump-sets to solar photovoltaic (SPV) pumps. The introduction of solar pumps for irrigation holds the promise of providing accessible and customisable energy solutions, especially in areas that lack access to the grid or receive electricity of inferior quality. Towards this end, the Government of India has introduced a scheme whose objective is to expand the installation of solar water pumps for irrigation. The official objective of the scheme, which is called the Pradhan Mantri Kisan Urja Suraksha Evam Utthan Mahabhiyan (PM-KUSUM)[1] scheme, is to achieve de-dieselisation of agriculture, enhanced water and energy security, augmented farm incomes, and reduced environmental pollution (MNRE 2021; Press Information Bureau 2023). The scheme includes a buy-back arrangement for surplus solar energy generated by the pumps and thus to further benefit small and marginal farmers. By May 2024, 352,138 pumps had been installed (MNRE 2024).

Solar irrigation in India has been promoted by different means, the most prominent being lowering the prices of solar PV panels and cutting solar power tariffs. The Solar Energy Corporation of India's latest competitive bidding process for determining solar power tariffs resulted in a record low bid of Rs 2.6 per kWh, representing an 80 per cent reduction from the tariffs above Rs 10 per kWh that prevailed in 2014 (Casey 2024; Singh *et al.* 2021). The Government of India has also instituted the Renewable Purchase Obligations policy, which mandates that State electricity distribution utilities procure a specified quota of renewable energy, with penalties imposed on those who do not do so. Solar pump sets for irrigation can help meet these mandated targets. Furthermore, electricity distribution utilities are expected to separate agricultural feeders from domestic feeders in rural areas, in order to better regulate agricultural electricity supply. Solar irrigation pumps are

[1] The name of the scheme translates as "The Prime Minister's Grand Campaign for Energy Security for and Upliftment of Farmers."

expected to help this process along by automatically limiting the hours of agricultural electricity usage to daylight hours. Some of the factors now encouraging the development of solar irrigation technology are thus the potential low cost of solar energy, State-level commitments to increase solar procurement, the development of grid infrastructure for generation and distribution, and the separation of agricultural feeders (Gambhir and Dixit 2018).

The objectives of this paper are twofold. First, the paper reports the results of a village-level study of the impact of solar-powered irrigation. Secondly, it seeks to estimate the annualised lifecycle costs (ALCCs) associated with solar irrigation, across varying technological and regulatory frameworks. The analysis pays special attention to the differential impact of the new technology on different classes of farmers.

A Brief Literature Review

Scholars have enumerated perceived benefits of solar irrigation pumps in India. Studies including Shah *et al.* (2017) and Shah (2019) proclaim solar irrigation to be a "game changer" as it is supposed to have the potential to break the "perverse nexus between electricity subsidies and groundwater depletion" while also providing uninterrupted daytime power supply. Shah (2019) and Verma *et al.* (2019) argue that the provision of free or subsidised electricity fosters inefficient energy usage, exacerbates groundwater depletion, and imposes a growing financial burden on state distribution companies (DISCOMs). They proposed a "Solar Power as Remunerative Crop" (SPARC) strategy, which incentivises farmers to replace grid-connected electric pump-sets with solar irrigation pump-sets, along with a guaranteed buy-back of surplus power generated. Studies have also demonstrated that solar-based irrigation may be more economical than diesel-based irrigation, particularly in remote areas, where refuelling and maintenance of diesel generators and unreliable power supply are not readily available (Raymond and Jain 2018; Foster *et al.* 2019; Gupta 2019; Xie *et al.* 2021; Pasupalati *et al.* 2022). Durg *et al.* (2024) suggest shifting away from viewing solar irrigation as a "silver bullet" and instead adopting a systems approach to design context-specific solutions that address risks, incentives, and capacity challenges. Other potential benefits associated with solar irrigation are the probable conservation of groundwater as well as reduction of carbon emissions. However, Balasubramanya *et al.* (2024) question the claim that solar-powered irrigation achieves net-zero emissions, suggesting that emissions reductions may be less than initially assumed considering all potential changes associated with its adoption. Regarding groundwater conservation, researchers have noted that unrestricted daytime access to solar power could accelerate groundwater extraction unless managed judiciously while balancing renewable energy-based irrigation and regulation of groundwater extraction (Closas and Rap 2017; Hartung and Pluschke 2018; Gupta 2019; Mantri *et al.* 2020; Rahman *et al.* 2021; Shah 2021).

Several studies have empirically examined the technoeconomic feasibility of solar irrigation (Bassi 2015; Sontake and Kalamkar 2016; Jadhav *et al.* 2020; Mantri *et al.* 2020; Hilarydoss 2021; Santra 2021) or have analysed its impact on food security and poverty (Burney *et al.* 2010; Gupta 2019). Bassi (2018) argues that solar technology does not generate significant welfare gains that justify heavy capital subsidies for farmers to switch completely from diesel and electric pumps, which are already heavily subsidised. Xie *et al.* (2021) point to the ambiguity of cost-effectiveness of solar PV, as it is sensitive to growth in installed capacities and diesel prices, emphasising the need for periodic review of costs and pricing in solar and energy markets for accurate evaluations. Jadhav *et al.* (2020) conducted a comparative ALCC analysis based on irrigation seasonality, pump sizes, and area connection density, concluding that off-grid solar PV pumps are more cost-effective when operated for more than 875 hours annually. Behavioural change has also been identified as a barrier to the adoption of renewable technologies (Mukherjee *et al.* 2020). Studies indicate that solar pump-sets can demonstrate lower efficiencies and pumping capacities compared to diesel pumps due to fluctuations in solar insolation (Abu-Aligah 2011; Closas and Rap 2017; Ali 2018; Aliyu *et al.* 2018). Some studies have also evaluated the technical limitations of solar irrigation, emphasising that the optimal sizing of the PV array for pumping depends on various factors such as solar irradiation, climatic conditions, panel efficiency, pump-set efficiency, pumping head, and daily water demand (Gopal *et al.* 2013; Harriss-White *et al.* 2019; Li *et al.* 2020; Hilarydoss 2021; Santra 2021).

However, there is limited discussion of the distributional impact of solar water pump-sets across socio-economic classes of cultivators in the literature. While studies have acknowledged the difficulty that small and marginal farmers face in accessing solar irrigation schemes, few have explicitly undertaken an evaluation of a solar irrigation scheme based on differentiated classes of farmers. Raymond and Jain (2018) in their report presented an economic model of factors affecting the costs associated with different types of irrigation pump-sets and then applied it to a series of deployment scenarios. Their model provided an analysis of the net present values (NPV) of the costs associated for farmers owning between 0.5–2 acres of land but did not cover large farmers. Gupta (2019) did an impact assessment of a solar project in Rajasthan for adopters and non-adopters of the project, but the energy costs were calculated and the analysis presented without accounting for differentiated classes of farmers. Jadhav *et al.* (2020) conducted a techno-economic comparison of five different technologies for powering irrigation pumps using the marginal cost of supply of electricity to estimate system costs. Although system-wide costs and calculation of ALCC is necessary from the perspective of policy-making for governments, utilisation of undifferentiated energy costs would fail to provide a tangible understanding of the requirement of subsidies and financial support for small farmers. Recent evidence suggests that the ownership of solar pumps, including both stand-alone units and those with net metering, tends to be concentrated among economically and socially advantaged farmers who can afford them, whether through government-coordinated programmes or private vendors (Closas and Rap 2017; Balasubramanya *et al.* 2024). Hence, it becomes imperative to identify and evaluate strategies to target solar irrigation to cultivators who can afford to purchase these pumps.

This paper undertakes an explicit evaluation of a solar intervention based on classes of farmers differentiated by size of landholding. We calculate the energy costs for beneficiaries and non-beneficiaries of a solar technology intervention across a range of farmers in two contiguous villages, Uchauli and Govindpur, in the Hardoi district of Uttar Pradesh. Our objective is to understand the dynamics of a shift to solar energy at the village level and the attendant impact on beneficiaries differentiated by socio-economic categories. Based on our results, we propose a design for targeted promotion of solar irrigation at the district level.

Method

Study Area and Solar Intervention

Uttar Pradesh had the highest number of operational agricultural holdings in India, with 23.82 million holdings and 17.45 million hectares under cultivation (Agriculture Census Division 2020). Despite the high irrigation intensity, agrarian inequality and lack of targeted institutional support for small and marginal farmers have hindered the development of cost-effective irrigation in Uttar Pradesh. Rawal and Swaminathan (1998) argue that the technological advancements needed for irrigation require substantial capital investment and involve high risks, which are significant barriers for small farmers (Modak and Bakshi 2017). Additionally, the widespread use of diesel pumps has imposed economic burdens on small farmers, who depend on informal rental markets for irrigation. The State faces a persistent electricity supply crisis, with many rural areas lacking access to reliable power. An independent survey by the Ministry of Rural Development (MoRD) found that over 14,700 villages in Uttar Pradesh lacked access to electricity (Tripathi 2018). The poor state of energy provision and the high costs of diesel-based irrigation underscore the potential for solar technology with interventions such as establishing solar mini-grids for household electrification and installing solar pump-sets for irrigation.

The solar intervention discussed in this paper was undertaken by a private entity.[2] A solar mini-grid was installed in the study villages for provision of domestic electrification and solar pump-sets for irrigation. The mini grid was used to power two solar submersible pump-sets of 7.5 HP capacity providing water for irrigation. All the fixed capital costs for implementation and construction of the project were covered using donor funding and were not charged to the farmers. Potential pilot sites for establishing solar mini-grids were assessed based on technical and economic parameters, including mini-grid size, solar panel capacity, and anticipated

[2] The project was initiated as part of a corporate social responsibility programme.

customer base. Uchauli and Govindpur in the Kachhauna block of Hardoi district, Uttar Pradesh, were identified as the most suitable sites due to the unreliable and uncompetitive nature of the electricity supply there as well as the potential for a larger customer base, including both domestic and agricultural connections. The mini-grid implemented a pay-per-use rental model, under which farmers could rent solar pump-sets on an hourly basis at a tariff of Rs 120 per hour, contributing to the operation and maintenance costs of the solar pump-sets. These contiguous villages were purposively selected for our study as they were the sites of solar intervention receiving irrigation from the mini-grid.

Households owning agricultural land were identified through census surveys conducted in both villages, supplemented by information from the concerned gram panchayats. A sample of households was selected from among both beneficiaries and non-beneficiaries of the scheme, excluding households not primarily engaged in agriculture (such as landless households and agricultural labourers). Structured information on socio-economic status, cropping pattern, energy use, irrigation costs, input use, and agricultural revenue was collected from both beneficiaries and non-beneficiaries of the solar pump-set scheme. Primary data collection included detailed survey schedules and discussions with farmers and other stakeholders involved in the solar intervention.

A total of 69 households in Uchauli and 70 households in Govindpur were surveyed for this study. While more than 45 households were registered in both villages as users of solar irrigation pump-sets, only 23 households utilised the pump-sets for irrigation during the rabi season. In each village, all beneficiary households were interviewed, and 50 households were selected from among the non-beneficiaries using a random sampling strategy. We used the Foundation for Agrarian Studies (FAS) schedule, supplemented by an additional energy survey focussed on energy availability and fuel use for irrigation and expenditures on the same, before and after the intervention, to create a baseline for comparison.[3] The study classifies farmers into size categories based on ownership of agricultural land. The classification, though different from the official categories, was selected so as to better reflect the land distribution in the study villages. The categories are as follows: farmers owning 0–1 acres, 1–2 acres, 2–4 acres, 4–6 acres, and 6–10 acres of land. It was observed that approximately 77 per cent of households included in the scheme were farmers with less than 2 acres of land. Only 6 households owned more than 4 acres of land.

Impact Assessment: Description of Variables and Hypotheses

To assess the short-term impact and effectiveness of the intervention, a pre- and post-evaluation was conducted, consisting of a baseline (ex-ante) study and a post-intervention (ex-post) study involving both beneficiaries and selected non-

[3] Available here: http://fas.org.in/wp-content/themes/zakat/pdf/Survey-method-tool/Schedule%20for%20Surveypercent20of%20Households.pdf.

beneficiaries from the same village, thereby confining the evaluation framework to the same agro-climatic zone to minimise variations due to geographical and regional factors. Data were collected before and after the intervention. Analysis of Covariance (ANCOVA) was used to examine the impact on outcome variables in the pre- and post-test research design. Focus group discussions and personal interviews with village residents revealed that the monthly tariff for irrigation services in the project area was prohibitive, particularly for smaller farmers (owning less than 2 acres of land). A comparative evaluation of the baseline with the ex-post data aimed to validate this observation and assess the impact of the intervention on beneficiaries.

The sample population was classified based on their exposure to the solar intervention as "Beneficiary" and "Non-beneficiary." The outcome variables of interests for this study were: i) hours of irrigation,[4] ii) costs of irrigation, and iii) wheat yield.[5] The null hypothesis for the test is that means of the dependent variables in the baseline year (2017) and the study year (2018) are equal, and the alternative hypothesis is that there is a difference between the means for the control and treatment groups. For the purpose of the statistical analyses, it was presumed that this treatment will affect the intensity of irrigation, cost of irrigation, and productivity. Consequently, the treatment units were expected to demonstrate the benefits of solar irrigation in the form of increased application of irrigation (measured as an increase in the total hours spent on irrigation), reduced cost of irrigation (in comparison to the purportedly more expensive diesel pump-sets), and increased productivity of agriculture due to increased irrigation.

Estimation of Annualised Life Cycle Cost (ALCC)

The annualised costs of different technological systems were based on the framework of Jadhav *et al.* (2020) and Solanki (2015) and were estimated as follows:

$$Lifecycle\ Cost\ (LCC) = \sum_{t=0}^{n-1} R_t \left(\frac{1+i}{1+d}\right)^t$$

where i=inflation rate, d=discount factor, Rt=expenditure or income in year t, n=lifetime of the component.

$$Annualized\ Lifecycle\ Cost\ (ALCC) = \frac{LCC}{\sum_{t=0}^{n-1} \left(\frac{1+i}{1+d}\right)^t}$$

[4] The intensity of irrigation was measured as the total number of hours of irrigation applied to the crops depending on the frequency of irrigation (in terms of the number of cycles of irrigation provided through the crop life and the number of hours of usage of the pump-set per irrigation cycle).

[5] Wheat is the major rabi (winter) crop in the region and was chosen for the analysis. The beneficiaries of the intervention started utilising the solar pump-set only in the rabi season, mainly for irrigating wheat. Thus, the total yield of wheat was evaluated pre- and post-intervention.

We calculated and compared the ALCC of each of the following options: i) energy-efficient electric pump (replacement of the electric pumps with star-rated energy efficient pumps by the Bureau of Energy Efficiency (BEE) under the Agriculture Demand Side Management (AgDSM) scheme); ii) off-grid solar PV pump; iii) pay-per-use model owned by private entity (at Rs 80 per hour); iv) government-owned public utility (at a flat rate of Rs 170 per HP per month); and v) grid-connected solar PV pump.[6] A description of assumptions in the estimation of the ALCC have been provided in Appendix Table 2.

Results and Discussion

Status and Costs of Irrigation

There are different systems of groundwater irrigation prevalent in the surveyed villages. Before the availability of solar-based irrigation, the most common source of irrigation was diesel-powered pump-sets, most of which were available only in the rental market. With access to solar irrigation, farmers started using a combination of diesel and solar pump-sets for irrigation. A total of 59 per cent of the farmers used only diesel as their primary source of fuel, 32 per cent used a combination of diesel and solar pump-sets, while 4 per cent used a combination of diesel and electric pump-sets. We observed significant variation in the average irrigation costs for each class of farmer based on source of fuel utilised, ownership (or lack thereof) of irrigation infrastructure, and cropping pattern.

Table 1 provides an overview of the average cost of irrigation incurred per acre and the total cost of irrigation as a share of the gross value of output (GVO) in the year of study, for households varying in extent of land ownership. Farmers owning less than 2 acres incurred higher costs of irrigation per acre in comparison to farmers who owned 6–10 acres (the largest size class in our sample), while they also received lower values of output per acre.[7] This can be attributed to the ability of larger farmers to extract greater productivity from their land and lower input costs due to their scale of production. While in absolute terms, larger farmers incurred higher irrigation costs, they could take advantage of economies of scale and invest more capital and inputs to realise greater value per unit of land compared to smaller farmers. Additionally, farmers (owning more than 4 acres of land) owned irrigation equipment and only paid fuel costs, whereas smaller farmers relied on informal water markets where hourly rental tariffs for diesel pumps were significantly higher than the cost of subsidised electricity.

[6] The financial and regulatory frameworks are based on prevalent technological options available, especially under the PM-KUSUM scheme corresponding to components B and C of the scheme.

[7] There was only one farmer owning more than 10 acres of land (30 acres) in the sample, who was excluded from the impact analysis.

Table 1 *Average cost of irrigation per household per acre and gross value of output (GVO) based on size class of agricultural landholding*

Ownership of agricultural land (acres)	Average cost of irrigation per acre (rupees per acre)	GVO per acre (rupees per acre)	Cost of irrigation as a percentage of GVO (per cent)
0—1	3707	7863	47
1—2	2619	16239	12
2—4	2533	4670	24
4—6	1268	13746	9
6—10	2705	48302	6

Impact Assessment Using Analysis of Covariance (ANCOVA)

There is widespread consensus that the productive use of electricity has the potential to become the key to poverty alleviation (Bensch *et al.* 2016). In the case of productive use of energy for irrigation, the overall impact of any intervention should aim towards increasing accessibility, cost-effectiveness, and productivity of energy usage. The intervention studied here is expected to provide direct benefits including improved accessibility, increased energy usage, reduction in expenditure on energy, intensified irrigation, leading to increased agricultural productivity and agricultural incomes. ANCOVA aids in the estimation of the true effect of the intervention by controlling for the effect of the pre-test data by including it in the analysis as a covariate.[8] Tables 2 and 3 provide a summary of the descriptive statistics and the results of the general linear regression model.

Table 2 shows the mean values for the outcome variables for both the pre-test and post-test conditions as well as the estimated marginal means.[9] Differences in pre-test and post-test mean values are not statistically significant. The estimated marginal means show minor differences pre- and post-intervention, which are not statistically significant, suggesting that even after adjusting for the values of covariates (outcomes variables before the intervention), the difference in means is not significant.

Table 3 indicates that the model does not produce any overall statistically significant effects for the time spent on irrigation (p-value=0.3379), cost of irrigation per acre (p-value=0.5034), and yield per acre (p-value=0.19301) based on the type of treatment received or farmer size category. In the case of the time spent on irrigation, while participation in the intervention did not have any effect on the means of the post-test values (F (2,50)=0.299, p=0.587), the size category to which a farmer belonged did have a significant effect on the outcome variable (F (2,50)=4.65, p=0.006), after controlling for the effect of the pre-test values. There was no significant interactive

[8] A preliminary analysis was conducted to check for the violation of the assumptions of normality, linearity, homogeneity of variances, and homogeneity of regression slopes.

[9] Estimated marginal means adjust for the covariate by reporting the means of the dependent variable for each level of the factor at the mean value of the covariate.

Table 2 *Descriptive statistics for the outcome variables for Uchauli and Govindpur, 2019*

Outcome of interest	Size category of farmers based on ownership of land (in acres)	Non-beneficiary (n=38)		Beneficiary (n=22)		Estimated marginal means	
		Pre-test mean	Post-test mean	Pre-test mean	Post-test mean	Pre-test mean	Post-test mean
Time spent on irrigation (hours)	0—1 acres	33.0	22.0	41.0	29.0	36.0[a]	32.0[a]
	1—2 acres	42.0	32.0	62.0	47.0	34.0[a]	34.0[a]
	2—4 acres	67.0	50.0	33.0	28.0	39.0[a]	38.0[a]
Yield of wheat (kg per acre)	0—1 acres	1096.1	1127.2	1197.4	1478.7	1056.8[a]	1406.6[a]
	1—2 acres	960.7	1076.5	1324.7	1687.2	1227.9[a]	1494.8[a]
	2—4 acres	1038.0	1048.3	1300.0	1667.0	1214.4[a]	1497.8[a]
Cost of irrigation (in rupees)	0—1 acres	5464	3943	3920	4676	3868[a]	5710[a]
	1—2 acres	4932	3426	8481	6109	3723[a]	4081[a]
	2—4 acres	4950	3612	7320	5560	3520[a]	4311[a]

Note: Covariates appearing in the model are evaluated at the following values:

a. Time spent on irrigation (Pre-test) = 45.13 hours.
b. Crop yield (Pre-test) = 1,120.967 kg per acre.
c. Cost of irrigation (Pre-test) = Rs 5,460.432.

effect between the control and treatment units and the size category to which a farmer belonged (F (2,50)=0.12, p=0.88). This indicates that the size of land holding affected the magnitude of irrigation provided. This seems fairly intuitive as it can be argued that smaller farmers provide less irrigation to crops owing to smaller operational holdings and limited capital, while larger farmers provide more irrigation as their per unit costs of irrigation are lower (as demonstrated in Table 1).

Table 3 *Summary of ANCOVA results for the dependent variables Uchauli and Govindpur, 2019*

Independent variable	Categorical variable	df	Mean square	F (2,50)	Sig.
Time for irrigation (in hours)	Type[1]	1	18.2	0.299	0.587
	Group[2]	2	282.3	4.650	0.006***
	Type *Group	2	7.6	0.125	0.883
Yield of wheat	Type	1	413392.4	3.3	0.074*
	Group	2	50019.2	0.402	0.671
	Type * Group	2	608.9	0.005	0.995
Cost of irrigation	Type	1	5476000.2	1.846	0.180
	Group	2	4412306.2	1.487	0.236
	Type * Group	2	3043535.4	1.026	0.366

Note: ***p<0.01, **p<0.05, *p<0.1

1. Type denotes participation in the intervention.
2. Group refers to the five land size categories.

The post-test values for wheat yields demonstrate that participation in the intervention (F (2,50)=3.3, p=0.074) showed a statistically significant result. There was a 90 per cent probability that mean yields of wheat for beneficiaries and non-beneficiaries would show differences after the intervention. This signifies that the utilisation of solar irrigation did lead to a moderate change in wheat yields for beneficiaries. The land size category to which a farmer belonged (F (2,50)=0.402, p=0.67) did not have any effect on the means of post-test values. There was no significant interactive effect between the participation in intervention and size category to which a farmer belonged (F (2,50)=0.005, p=0.96).

Comparable results were observed for the cost of irrigation with post-test values showing no significant interactive effects of participation in the intervention and size category of beneficiaries and non-beneficiaries (F (2,50)=1.026, p=0.37). The current user tariff for solar pump-sets had no discernible impact on reducing costs of irrigation; on the contrary, beneficiaries of the project who used solar pump-sets paid a higher cost of irrigation. The costs of operating the solar pump-sets are comparable to the costs of operating diesel pump-sets. While there were differences in the costs of irrigation for beneficiary and non-beneficiary farmers in absolute terms, the differences were not statistically significant.

To summarise, no significant measurable changes were observed on account of the intervention in respect of the time spent on irrigation and costs of irrigation, while wheat yields showed a marginal increase. No noticeable changes were seen in cropping pattern including the area under cultivation of all major crops including paddy, wheat, mustard, maize, and fodder crops. The only measurable change was an increase of 0.4 per cent in area under cultivation of vegetables, mainly for farmers owning more than 4 acres of land. Shifting towards more water-intensive and resource-intensive high-value crops requires more capital, which is not readily available to smaller farmers (less than 4 acres) who formed a majority of the project beneficiaries. Since the study region already had a high gross irrigated area, the intervention did not produce any significant change in terms of the irrigated area or the intensity of irrigation. The common sentiment expressed by the respondents, both beneficiaries and non-beneficiaries, was that the excessive cost of utilising the solar pump-set was the biggest deterrent to large-scale adoption.

Socio-Economic Feasibility of Solar Irrigation

There was almost complete consensus on the increased effectiveness of solar pumps, with respondents claiming that solar pump-sets were more energy efficient and extracted larger volumes of water at a faster rate compared to diesel pump-sets. However, solar pump-sets were being used in conjunction with diesel pump-sets and had only managed to complement diesel use, not substitute it completely. Respondents also acknowledged that owing to its cost effectiveness, grid-based electricity remained the first preference for irrigation. During the focus group discussions, some of the respondents complained about the tediousness of irrigation using solar pump-sets which required physically moving the pump-set across the fragmented pockets of land they owned, an extremely time-consuming and cost inefficient process. They seemed willing to pay a high user charge for utilising the pump-set, provided the pipelines were extended closer to their fields, thereby reducing the time spent on irrigation. The consumers reported that they had expected enhanced services and better incorporation of technology after paying current levels of high user tariffs. There remains a potential for solar irrigation in the study area due to the unavailability of electricity connections. However, solar irrigation can become viable only if the costs are economically feasible, especially for farmers with small-sized landholdings as a majority of them use self-owned or rented diesel pumps which are inefficient and highly unprofitable.[10]

Another method of assessing the socio-economic viability of solar irrigation would be to compare the costs of solar irrigation to the costs of using electric and diesel pump-sets (see Table 4). The results substantiate the phenomenon of "economies of scale" as there is a reduction in per acre costs as the size of landholding increases. Larger farmers with access to electric pump-sets could use subsidised electricity and therefore irrigate their land at much lower costs than those using pump-sets powered by other fuel sources. The cost of irrigation for a farmer owning less than 1 acre of land was 52 per cent higher than the cost of irrigation for a farmer owning more than 6 acres of land. There was only one farmer (owning less than 1 acre) who had completely shifted to using solar irrigation for irrigating wheat, even though the cost of using solar was the highest among all fuel options.

To assess the economic viability of solar irrigation, a comparative analysis of costs for irrigation with different sources of fuels was conducted (Table 5). To illustrate the implications, we selected two cases:

1. A farmer owning 1.5 acres who had shifted completely to utilising solar from diesel (beneficiary)
2. A large farmer owning 30 acres of land and a 7 HP electric pump (non-beneficiary) and 30 acres of land.

As evident from Table 5, in the case of the smaller farmer (owning 1.5 acres), costs were lowest with subsidised electricity and highest with the hourly tariffs of Rs 120 for diesel- and solar-based irrigation. Even the cost of unsubsidised electricity (estimated using average cost of supply) was lower than that of diesel and solar

[10] While 45 farming households had registered themselves as users of solar irrigation pump-sets based on the list provided by the implementing agencies, it was observed that only 23 households utilised the pump-set for irrigation once the pump became operational. One of the two most common reasons for the under-utilisation of the pump-set was the prohibitive hourly tariff (Rs 120 per hour). The second was that the command area of the pump-set was limited, preventing use by some farmers. A total of 30 per cent of the non-beneficiaries were keen to utilise the pump-sets but could not do so as the current pipe lengths restricted the area of operation.

Table 4 *Average cost of irrigation per household, per acre, for different sources of fuel used for irrigation based on agricultural land ownership*, in rupees per acre

Ownership of agricultural land (in acres)	Diesel	Diesel+Electric	Diesel+Solar	Electric	Solar
0—1	3880	1650	3523	-	4800
1—2	2225	2300	4035	-	4160
2—4	2073	-	3608	-	-
4—6	-	-	1267	-	-
6—10	-	2705	1448	1767	-

irrigation. For the cost of solar to be even close to the cost of unsubsidised electricity, the hourly tariff charged has to be as low as Rs 21 per hour, while it has to be less than Rs 6 per hour to be comparable to subsidised electricity.

For the large farmer (owning 30 acres), the costs of moving to solar irrigation seem advantageous as the operational cost of running a solar pump is lower than that of an electric pump. Even though the total cost of irrigation for the farmer would be higher in absolute terms since he/she would irrigate a larger piece of land, they would be able to optimise time spent on irrigation because of scale and consequently realise more output. Whereas the marginal farmer is bound to pay the hourly tariff, even though he/she might be able to irrigate their land in less time due to the reduced scale of operation and smaller land size. Thus, the costs of solar irrigation can become economically viable for large farmers as they would be able to take advantage of the economies of scale, while for farmers operating on smaller and fragmented pieces of land, shifting to solar remains expensive in comparison to using subsidised and even unsubsidised electricity provided at the actual cost of supply.

Comparison of ALCC for Different Technological and Regulatory Models

Next, we assess the system-wide annualised lifecycle costs (ALCCs) for the following configurations: i) energy efficient electric pump; ii) off-grid solar PV pump; iii) pay-per-use model owned by private entity (at Rs 80 per hour); iv) government-owned public utility (at a flat rate of Rs 170 per HP per month comparable to the current agricultural tariff in Uttar Pradesh); and v) grid-connected solar PV pump. Figure 1 shows the costs associated with various solar technologies in comparison to the cost of electricity – illustrated for a 5 HP pump-set. The estimates of ALCC for different technologies demonstrate that energy efficient electric pump-sets might still be cheaper than all configurations of solar energy. The use of the pay-per-use model of solar irrigation is found to increase substantially with increasing energy consumption, becoming economically infeasible for all stakeholders involved. Grid-connected pumps seem

Table 5 *Estimated costs of irrigation per acre using different fuel sources*, in rupees per acre per year[11]

Case	Cost of irrigation using an electric pump (subsidised tariff of Rs 1.7 per kWh for energy efficient pumps)[12]	Cost of irrigation using an electric pump (average cost of supply of Rs 6.10 per kWh)[13]	Cost of irrigation using a diesel pump (hourly tariff of Rs 120 per hour)	Cost of irrigation using a solar pump (hourly tariff of Rs 120 per hour)	Cost of irrigation using a solar pump (hourly tariff of Rs 80 per hour)	Cost of irrigation using a solar pump (hourly tariff of Rs 30 per hour)
Farmer owning 1.5 acres	3080	1104	4160	4160*	2773	1040
Farmer owning 30 acres	1767*	6339	1084#	1600	1067	400

Note: *Actual costs based on empirical data.
#The estimated costs of irrigation do not include installation costs and cost of the pump. Since the large farmer owns another diesel pump, it would be cheaper for him/her to utilise diesel-based irrigation.
The estimated costs of irrigation for other sources of energy have been calculated assuming that the number of hours of irrigation provided by the farmer remains the same for all fuel sources. It was assumed that the number of hours of irrigation provided by both farmers, the farmer owning 1.5 acres (25 hours)[14] and the larger farmer owning 30 acres (400 hours), in the agricultural year remained the same across different fuel sources.

[11] It is assumed that 1 HP = 0.746 kW.
[12] Uttar Pradesh Power Corporation Limited (UPPCL) (2019).
[13] Asian Development Bank (2020).
[14] The farmer does not provide any irrigation in the kharif season and is totally dependent upon pre-monsoon rainfall.

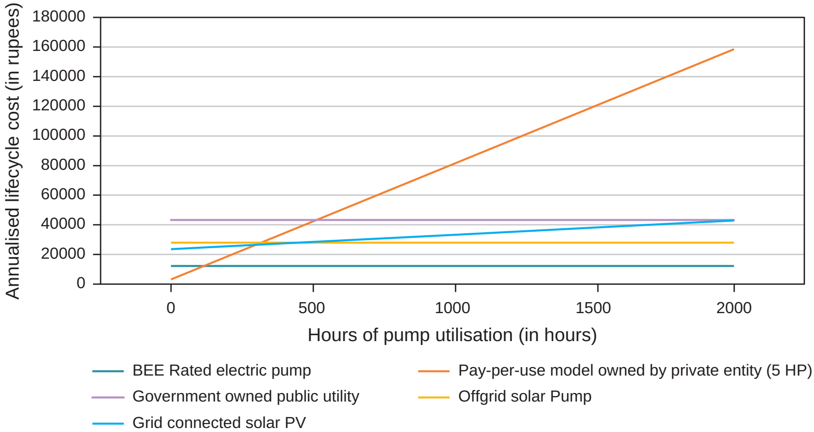

Figure 1 *Estimation of ALCC for different possible technological models for a 5 HP pump-set*

viable when they are used for less than 500 hours annually, but at higher levels of consumption, solar off-grid pumps impose lesser cost.

Table 6 provides an overview of the ALCC for different stakeholders including costs for cultivators as well as the capital subsidy that the government would need to provide per pump-set, signifying that from the government's perspective, in terms of the subsidy burden incurred per pump-set, grid connected pump-sets are more economical. However, while grid-integrated solar irrigation pump-sets seem viable, other practical considerations such as the complexities associated with determining cost-reflective tariffs, higher upfront capital costs, and poor metering and collection render it unfeasible, as also argued by Jadhav *et al.* (2020).

To provide some context to the district-level potential that solar irrigation might have, it is essential to undertake a comparison of capital and operational costs of various

Table 6 *Estimation of ALCC for relevant stakeholders*, in rupees per pump-set

Different possible scenarios for provision of capital subsidies	ALCC for farmer based on size of pump-set		ALCC for government expenditure for provision of capital subsidy per pump-set	
	5 HP pump	7.5 HP pump	5 HP pump	7.5 HP pump
Off-grid solar PV pump (at 40 per cent state subsidy and 30 per cent Central Finance Assistance)	13074	16474	18041	23141
Grid connected solar pump-set	5039—31295	8869—37869	17765	22530

Note: Capital costs have been calculated using benchmark costs available on the PM-KUSUM portal. Costs have been estimated for a range of 0–2,000 hours of operation of a pump-set.

technologies for cultivators belonging to different socio-economic classes as well as the additional subsidy burden it would mean for the government. On the basis of the analysis carried out in the preceding section, it has been shown that farmers owning more than 6 acres of land have the capacity to bear the upfront capital costs associated with solar and also obtain lower per unit costs of irrigation owing to greater scale of operation as well as greater efficiency, while for smaller farmers, subsidised electricity remains the most cost-effective option.

We propose a targeted scheme for the promotion of solar energy in which farmers owning more than 4 acres of land are provided with solar pump-sets. Meanwhile, farmers owning less than 4 acres should receive subsidised or partially subsidised electricity supply to ensure that the financial burden of shifting to solar energy does not fall upon them. The comparison has been provided for off-grid solar pump-sets of size 5 HP which might be targeted for farmers owning 4–6 acres and 7.5 HP pumps for farmers owning more than 6 acres of land.[15] The ALCC for farmers for the aforementioned pump-set sizes was estimated to be Rs 13,074 and Rs 16,474 per pump-set per farmer (see Table 6). Similarly, the ALCC for farmers owning less than 2 acres was estimated to be Rs 2,704 per pump-set at a subsidised tariff of Rs 1.7 per kWh, while for farmers owning between 2–4 acres, the ALCC was estimated to be Rs 3,069 at a partially subsidised tariff of Rs 3.5 per kWh.

Table 7 provides estimates of the subsidy that central and state governments would have to provide in order to implement a targeted scheme for the promotion of solar irrigation in Hardoi. The results indicate that for farmers owning more than 6 acres, the capital subsidy required for the promotion of solar is approximately double the amount of annual cross subsidy provided for electricity in Hardoi district. Consequently, supporting the shift to solar pump-sets for farmers owning more than 6 acres would be beneficial as the expenditure incurred from paying the capital subsidy can be recovered in two years (as the government is not liable to provide annual cross subsidies). On the contrary, for farmers owning less than 4 acres of land, the capital subsidy burden for financing solar pump-sets would be substantially higher than the annual cross subsidy paid to the agricultural sector for electricity use. Thus, implementing a shift to solar for farmers owning less than four acres of land remains economically unviable since electricity remains the cheapest option for the provision of irrigation, both from the perspective of the DISCOM and the farmers.

The evidence suggests that solar technology is currently unaffordable for farmers owning less than 4 acres of land, and designing a differentially targeted policy would serve the two-fold objective of preparing the ground for engendering an

[15] Since Hardoi has poor grid infrastructure and is largely dependent on diesel pump-sets for irrigation, solar off-grid pump-sets would be a viable option since the groundwater table is also higher compared to other arid and semi-arid regions.

Table 7 *Subsidy incurred by government agencies for the implementation of proposed targeted scheme*

Size class of cultivators based on ownership of land (in acres)	Benchmark costs for solar pumps (in Rs per pump)	CFA (central plus state) available (Rs per pump)	Capital subsidy (central plus state) burden for promotion of solar (in millions)	Annual cross subsidy for electricity provided by state government per farmer category (in millions)
Farmers owning between 6—10 acres (7.5 HP)*	352500	246750	100.7	40**
Farmers owning between 4—6 acres (5 HP)*	236500	165550	1544.7	681.6**
Farmers owning less than 4 acres (3 HP)*	168300	117810	70481	1456.8**

Note: The capital subsidy burden was estimated using data for the number of farmers across size categories (based on land ownership) from the Agricultural Census, 2015–16.
*The figures in brackets indicate the size of the solar pump-set assumed for the purpose of estimating the benchmark costs and CFA.
**The number of units consumed by farmers owning between 6–10 acres, farmers owning between 4–6 acres, and farmers owning less than 4 acres in a year is assumed to be 30,000, 15,000, and 500 kwh per year respectively.

energy transition towards solar irrigation and assuring the provision of affordable energy for farmers with small land holdings.

Conclusions

Economic growth is critical for sustained poverty reduction in low-income economies. Significant shifts from "business-as usual" methods are needed to ensure that developing countries move towards low-carbon trajectories. However, such shifts, especially in energy technologies, often entail high upfront costs in terms of infrastructure, technology adoption, and capacity building. Public expenditure is essential to bridge this financial gap and to help design policies that provide the regulatory and market incentives that ensure the successful deployment and uptake of solar irrigation. The study is a preliminary step towards assessing the implications of such shifts and the heterogenous and unequal impact of changes in energy utilisation on different socioeconomic classes of farmers. More specifically, it is an attempt to evaluate the short-term implications of a shift to solar energy for farmers across different sizes of land holdings based on a case study of two contiguous villages in Hardoi district in Uttar Pradesh.

Since the study villages were already irrigated and since farmers in the villages were already cultivating water-intensive crops such as rice and wheat, the solar intervention did not create a perceptible impact either on gross area under irrigation or on cropping pattern in the villages. The average yield of wheat rose as a result of the intervention, thus demonstrating the potential role of assured solar irrigation in increasing agricultural productivity. The study showed that the cost of irrigation was an important, often crucial, factor in the adoption of solar irrigation in the study region.

The study also provides an assessment of the annualised lifecycle costs (ALCCs) associated with varying technological and regulatory models being implemented by Central and State Governments in India. The results establish that solar irrigation remains expensive in comparison to subsidised electricity supply, in particular for farmers owning less than four acres of land.

Increased diffusion and penetration of decentralised solar irrigation is only possible if a regulatory environment is created in which the installation and capital costs of the technology are subsidised, thereby reducing the overall energy price of the technology. One of the key obstacles for farmers with very small land holdings is the lack of finance. These farmers lack the capacity to gain access to mainstream financial institutions as the associated risks, collateral, and transaction costs are too high for them to bear. This paper proposes the initiation of a targeted scheme for utilisation of solar pump-sets by farmers who have the means to bear the high upfront costs and extract greater returns resulting from the increased scale of application of irrigation. Such a scheme would ensure that the burden of shifting to solar technologies would not be on farmers who already face other problems such as low efficiency and productivity because of the structural inequalities prevalent in the agricultural sector. The results also indicate that the amount of land operated is a determinant of the efficacy of the intervention in terms of cost reduction. For small farmers, subsidised and even unsubsidised grid-based electricity seemed to be the most cost-effective means of irrigation. We recommend that schemes should be targeted on the basis of size of land holding, with smaller farmers being allowed greater access to the benefits of subsidised grid-based electricity.

Ethics Declaration

Informed consent was obtained from all human participants for the purpose of data collection. The privacy rights of all the human participants of the study were observed, and anonymity was maintained in compliance with relevant institutional guidelines.

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