Harnessing the sun for an evergreen revolution:A study of solar powered irrigation inBihar, India

Avinash Kishore(a.kishore@cgiar.org), PK Joshi (p.joshi@cgiar.org), and
Divya Pandey[1] (d.pandey@cgiar.org)

International Food Policy Research Institute (IFPRI)
NASC Complex, CG Block
Dev Prakash Shastri Road, (Opp. Todapur)
Pusa, New Delhi 110012, India
Fax: +91 11 2584.8008 / 2584.657

Abstract

In a novel experiment in 2012, Government of Bihar in India revived 34 non-functioning public tubewells by connecting them to solar panels. We randomly selected 16 tubewells and tracked their performance for a year using data collected from tubewell operators and irrigators. To the best of our knowledge this is the first study on field performance of solar powered irrigation pumps, in Asia. We find that solar powered pumps are easy to use and manage, and work well across all seasons. Access to irrigation from solar pumps led to increase in productivity of wheat and paddy—the two main crops in Bihar. During a severe drought, farmers could grow paddy in the entire area under solar irrigation, while nearly 40 percent of other land was left fallow due to water scarcity and high cost of irrigation. Thus, solar pumps can help make agriculture resilient to weather fluctuations. They can also help reduce emission of greenhouse gases and other pollutants from fossil fuels used to power irrigation pumps. We recommend changes in the water prices being levied under the existing solar irrigation model. We also argue that for tubewells to be viable in Bihar, they should be powered by solar energy.

---

[1] Corresponding author

1. Introduction

India and other developing countries are increasingly promoting solar pumps for meeting the irrigation needs of farmers. In India, the Ministry of New and Renewable Energy (MNRE) has proposed to install over 30,000 solar pump-sets per year under the Jawaharlal Nehru National Solar Mission (JNNSM) (MNRE, 2014). Various state governments too have initiated schemes subsidizing solar irrigation pumps[1].In other countries, efforts for solarization of pumps are being spearheaded by international development agencies. In Bangladesh, for instance, the World Bankthrough its ten million dollar grant to the government, aims to bring about 8,700 hectare of land under solar irrigation (World Bank, 2015).

In parts of rural Asia and Africa, where power supply from the grid is poor or non-existent, such efforts for solarization of pumps aim to reduce farmers' distressby providing increased access to affordable irrigation.Solar pumps have long lifetimes, need minimal attendance and maintenance, and have near zero operational cost. Several studies in India and in other countries show that in spite of much higher capital cost, the lifecycle cost of solar powered pumps is lower than that of liquid-fuel-based pumping systems (Kolhe et al., 2002; Odeh et al., 2006;Meah et al., 2008; Kelley et al., 2010;GIZ, 2013). Electricity from solar panels now costs only half as much as that from diesel generators (DGs) in India, even when diesel is subsidized[2]. Further, solar energy has an additional advantage over fossil fuels: it provides emissions free power using a renewable source of energy. Kumar and Kandpal (2007) estimate that for daily solar radiation availability of 5.5 kilo watt-hour per square metre(kWh/ m^2)[3], a 1.8 kilowatt-peak (kWp) photovoltaic (PV) pump system will have a net annual carbon mitigation potential of 2085 kilograms (kg), compared to a diesel operated pump system with the same specifications.

Encouraged by increasing affordability of the technology[4], many international development agencies, are promoting solar pumps in developing countries (See Ramos and Ramos, 2009; World Bank, 2015). In India, almost all major states have initiated subsidy schemes to promote solarpumps. Still, hitherto, most studies assessing the cost-benefit analyses of solar powered pumps have been based on engineering approaches and havenot used empirical data from actual adopters.A study by Burney et al. (2010) is an exception, where they study the functioning of solar-powered *drip* irrigation in Sudano-Sahel in West Africa. But, to the best of our knowledge no studies have documented the performance of solar-powered *tubewells* in farmers' fields.Our paper attempts to fill this gap by presenting data collected by us from 160 solar pump users in the Indian state ofBihar.We thus, contribute to the PV technology and irrigation literature, by presenting the first careful study of performance of solar pumps in farmers' fields in India and one of the first in the world.

The rest of the paper is organized as follows. Section 2 introduces the solar pump scheme introduced by the Government of Bihar in our study area, anddescribes the data and methodology used in the study. We present the resultsand discuss their significance for energy and irrigation policies in section 3. Section 4 concludes the paper with policy implications of our findings for the state of Bihar, where solar pumps can play a useful role in promoting irrigated agriculture.

2. Methods

2.1.Solar-powered public tubewells in Nalanda, Bihar

About 90 per cent of the farmers in Bihar — an agrarian state in northern India — are small and marginal. Poor electricity supply and high diesel costs often force farmers to practice deficit irrigation (Shah, 2007; Kishore et al., 2014). In March 2012, the Minor Irrigation Department (MID)ofthe Government of Bihar started a pilot project where 34 non-functioning PTWs in 20 villages of Nalanda district were connected to solar panels by Claro Energy, a private company that offers off-grid solar power solutions for power deficit regions. They were established by the MID in 2004-05 under a long-running state government's project called the State Tubewell Project. Each PTW has been built by the MID on 100-110 square meter of donated private land and operated by a group of eight neighbouring farmers formed into a water users' association (WUA). The land donor is often the secretary and the executive head of the WUA and is mainly responsible for its day to day operation, water allocation, and water-fee collection. He charges water buyers a government-fixed irrigation service fee (Shah and Kishore, 2012).

These tubewells are equipped with 7.5 horse-power (hp) electric pump-sets. Since the grid power supply in rural Bihar is poor and inconsistent, these electric pumps were connected to dedicated DGs.Almost all DG poweredPTWs, however, fell into disuse because they were highly expensive to operate. A typical generator burned around threeliters of diesel per hour of operation. At this rate, the cost of irrigation worked out to be rupees (Rs) 3200-3600 per hectare perirrigation. In 2011-12, the MID invited Claro Energy to install solar panels to replace the inefficient diesel generators for 34 PTWs in Nalanda district. The rehabilitated community tubewells have been in operation since *Rabi*(winter season)2011-12. These tubewells are around 300 feet deep and have water discharge capacity of about 60-70 cubic meters per hour. They are fitted with outlet pipes of eight inch diameter. Three buried distribution pipes, each of 300 feet length, convey water to fields around the tubewell.

After solarization, each pump now draws power from six arrays, each with six solar panels. One solar panel can generate up to 235 Wp. Thus, the combined array of 36 panels can produce peak power of 8.4 kWp to operate the 7.5 hp pump. A variable frequency drive that can use power supply between 250 to 440 volts, convertscurrent producedby solar panels into three phase alternating current (AC) and operates the pump. The water discharge rate of the pump varies with the intensity of the incident solar radiation. Solar panels are mounted at a height of 5.5 feet with a distance of 22 feet between two arrays to make sure that when panels are tilted to maximize exposure to sun, they do not shadow each other. Together, the six arrays require about 110 square meter of open space with unrestricted exposure to sun. Depending upon the time of the day, the season and the crop, the solar pump may take anywhere from 16 to 33 hours to irrigate a hectare of land. Pumps usually function for approximately six to nine hours a day, depending upon the season.

The management of the tubewells and the collection of irrigation fees is ideally the responsibility of the WUA.In practice, though, the secretary of the WUA performs these activities himself or through his hired operator. The tubewell operator maintains a logbook with names of the farmers using the solar pumps for irrigation, the number of times and hours each farmer uses the pump, and the area irrigated by each farmer. Farmers pay a subsidized irrigation fee of around five Rs per *katha*[5] to the operator, which is kept for any future expenses relating to the repair and maintenance of pumps. These solar pumps in Nalanda are embedded into a pre-existing institutional setting that does affect the full impact of the technology.

2.2.Sampling and data

Of the 34 solar pumps that Claro Energy had installed in Nalanda,we randomly selected 16for our study. These 16 pumping systems are spread across 14 villages in 11 blocks of Nalanda district in Bihar. We first met with the operators of solar powered PTWs and collected names of all farmers who had land in the command area of the PTWs from the official registry of beneficiaries maintained by the pump operator. The 16 pump-sets together irrigated lands of 594 farmers in 2012-13. The total number of beneficiaries in the command area of solar PTWs varied between 20and48. We selected tenfarmers randomly from the list of beneficiaries for each of the sampled PTW. For each PTW in our sample, we also selected fivefarmers who had their lands close to the command area of the solar pump, but were not irrigated by it. Not a single plot or parcel of land of these 80 farmers received any irrigation from the PTWs. Altogether we have a sample of 240 farmers: 160 who irrigated at least some of their land with solar pumps and 80 who did not irrigate any land with solar pumps.

We carried out five rounds of surveys with these farmers in crop-year 2012-13. The first survey was carried out at the onset of the *Rabi* season in 2012-13. In this round, we collected data onfarmer characteristics and plot-wise application of input, from all the 240 farmers in our sample.We followed this survey with two more visits during the *Rabi* season where we collected more data on use of inputs along with hours of irrigation from different sources. Repeated visits in the same season led to greater accuracy in recall data on use of irrigation and other inputs. In the third and the final round of survey in *Rabi* 2013, we also collected data on crop output realized.

Landholdings in Bihar are highly fragmented (Sharma, 2005).A typical farmer in our sample had more thantenparcels of land. For each of the 160 beneficiaries of solar pumps, we collected parcel level data on use of inputs and the output realized from their three largest parcels in the command area of the pump (solar plots) and one parcel that was closest to the boundaries of the command area, but was not irrigated by the solar pump (non-solar plots). For the 80 non-beneficiaries, we collected data fortheir one largest plot closest to the edges of the solar pump's command area. Thus, we have a control plot for each beneficiary that allows us to estimate the difference made by access to affordable irrigation. The non-beneficiary farmers serve as a second control group. We carry out both within-farmer and between-farmer comparisons of solar and non-solar pump irrigated plots.

Originally, we had planned to study the impact of solar pumps only in the winter season, which is the main season for irrigated agriculture in Bihar. Agriculture in *Kharif* is more dependent upon monsoon rains. 2013, however, turned out to be a drought year in Nalanda — there wasadelay in the onset of monsoon and a25 per cent shortfall was recorded in the monsoon rains from the long-term mean of the district(IMD, 2015).The shortfall was more than 40 per cent in the critical months of June and July when paddy is sown and transplanted (IMD, 2015). Analysis of data from recent years shows that droughts significantly affect both cropped area and crop yields in *Kharif*season in Bihar (Kishore et al., 2014). Therefore, we decided to extend our study to the *Kharif* season to assess if access to cheaper irrigation from solar pumps helps farmers in a drought year. For the*Kharif* season, we collected data on crop area not only from the selected plots, but for the entire operational holding of both beneficiary and non-beneficiary farmers. We carried out two rounds of surveysin *Kharif* 2013—first around the time of transplantation of paddy(August-September, 2013) and the second, after the paddy harvest (in early January, 2014).We present results on the performance of solar pumps in *Rabi* and *Kharif* seasons separately in the paper.

In each of the five rounds of survey, we also carried out detailed interviews with pump operators to collectmonthly data on the number of hours of solar pump operation, area irrigated by the pump, number of farmers whose land was irrigated, the number of days that the pump did not run and reasons thereof (no sunlight, no demand for irrigation or fault in machines) from their log books. We also collected detailed data on any instances of break-down in the PV system, costs incurred and days taken to repair the break-down. After five rounds of survey, we had monthly data on operational details of these 16 solar pumps from January to December 2013. This data allows us to understand the reliability of solar pumps as a source of irrigation in different seasons of the year in rural Bihar and issues involved in its operation and maintenance. This was perhaps the first such effort, anywhere in the world, to collect detailed field data on the functioning of solar pumps, spanning over a period of one year and two major cropping seasons.

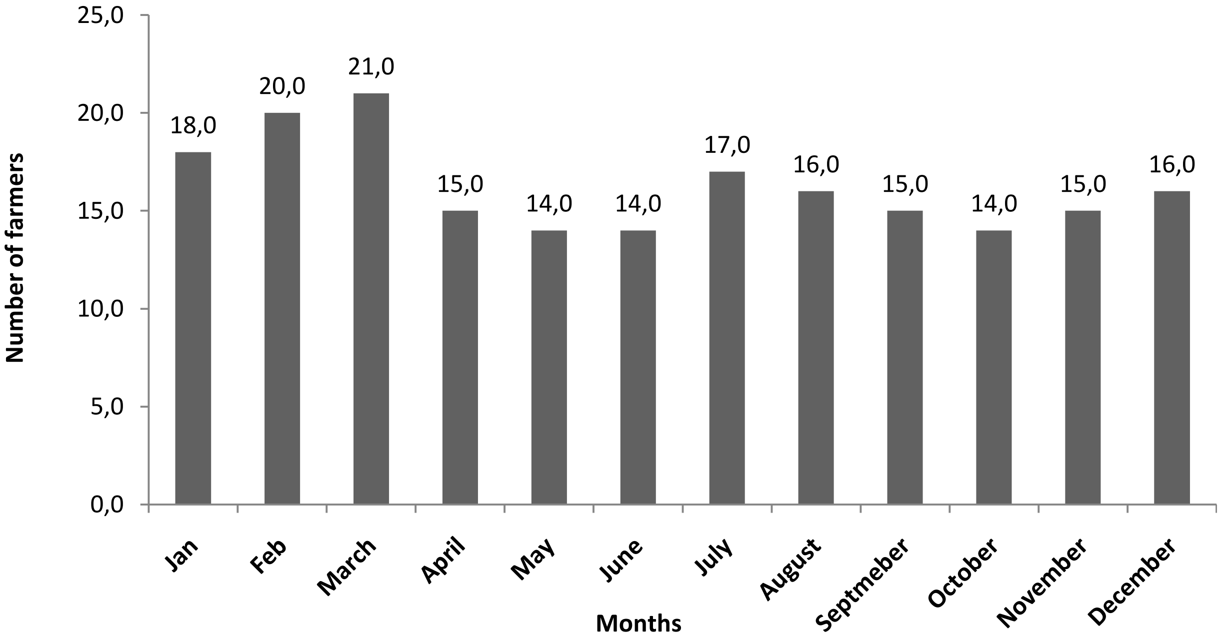
3. Results and discussion

3.1.Working of solar powered public tubewells

*Command area and hours of functioning of solar pumps in 2013:*An average PTW had a designedcommand area of 8.35 hectares. This is the area that could potentially be irrigated by the tubewell if the network of buried pipelines for conveying water to the field was in a perfect state. This, however, was not the case and the actual area served was limited to sixhectares in *Kharif*and fivehectares in *Rabi*. The average number of farmers using solar pumps in a command area varied between 16 in *Kharif* and 18 in *Rabi* (Figure 1).On an average these 16 pumps worked for 900 hours in 12 months (600 to 1300 hours). Farmers used solar pumps most intensively in the *Kharif* season to irrigate paddy affected by drought in that season (Figure2). Summer cropping is uncommon in Nalanda as in the other districts of Bihar, owing to increased irrigation requirements (and costs) during the season. Indeed,farmers used pumps only lightly duringthe summer (*garma*) season. It is likely that cropped area in summer season will increase, once farmers adjust to the availability of affordable irrigation from solar pumps.

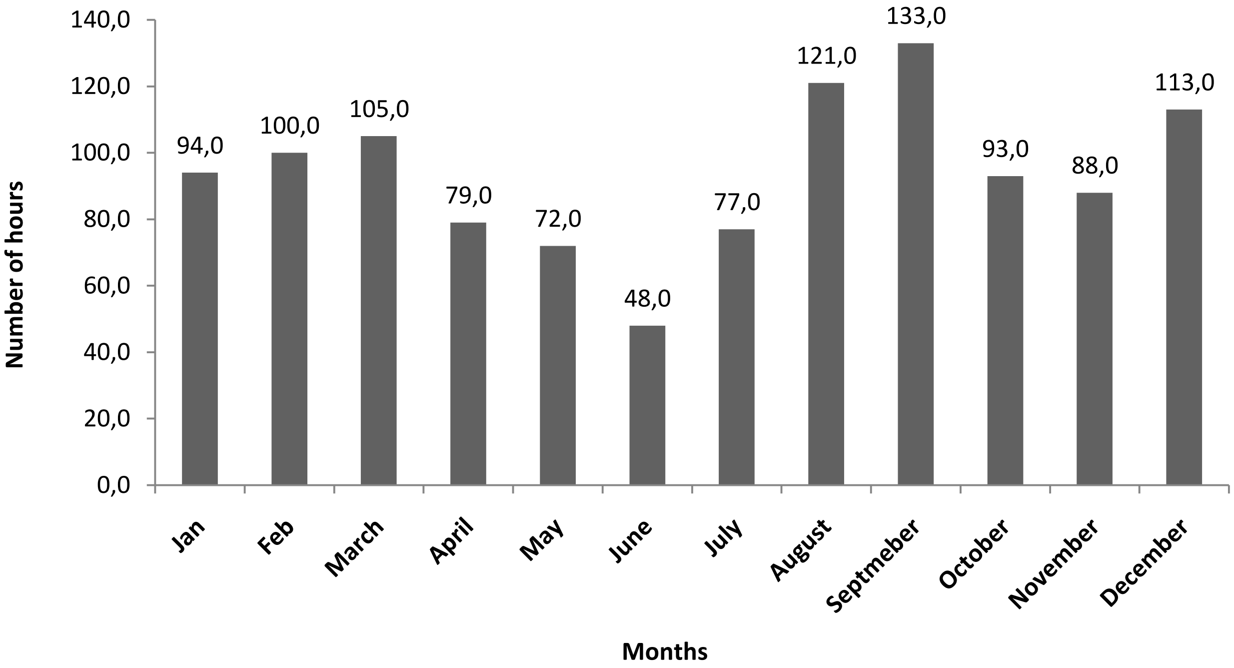
Almost all tubewell operators strongly felt that an investment of600 US dollars (USD) to 3000 USDin the repair and construction of new buried pipeline network for water distribution would increase the effective command area of solar pumps, increase capacity utilization of pumps and nearly double the number of beneficiaries. They, however, were not keen to make this investment themselves because they believed that it was the duty of the MID. Instead, they had made ad hoc arrangements where they connected water outlets to long collapsible plastic pipes to irrigate land that lay beyond the reach of buried water distribution pipes. All pump operators, we surveyed, used these collapsible pipes to extend the command area. However, the topography often limits the potential to expand command area with collapsible pipes.

Figure 1 - Average number of farmers in the command area of a solar pump, who irrigated their lands from solar pumps in 2013



Source: Primary data collected by authors in Nalanda, Bihar.

Figure 2 - Average hours of operation of solar pumps across months in 2013



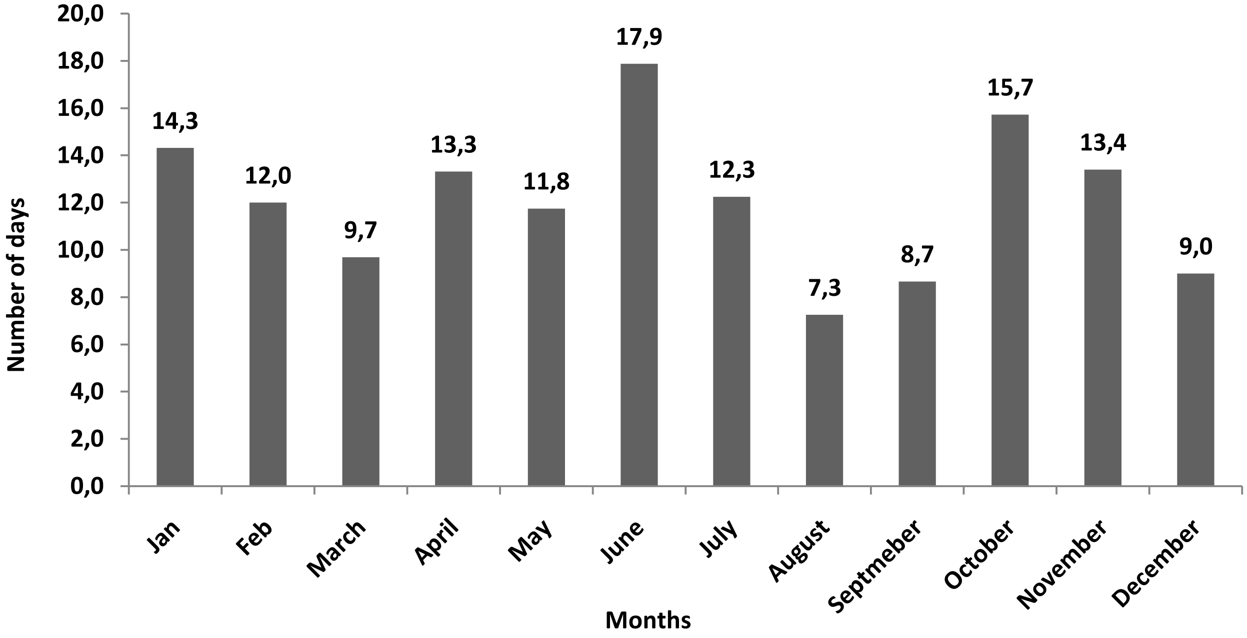
Source: Primary data collected by authors in Nalanda, Bihar.

*Irrigation rates:*The discharge rates of solar pumps vary a lot across hours in a day and across seasons. Farmers, therefore, pay for irrigation by per unit area and not by hours. The rate fixed by the MID was Rs320 per hectare per watering in *Kharif* and summer seasons, and Rs 400 per hectare per watering in the winter season. Irrigating with own diesel pump costs around more than twice as much and the cost of irrigation from a rented diesel pump is even higher.

We believe that the MID set a water tariff too low for solar pumps. Offering such high subsidies to only a fewpromotes inequity. With such low tariffs, pumps would not collect enough resources for major repairs and maintenance. Higher water tariff would also generate enough resources to systematically extend the command area and cover the depreciation cost.

*Reasons for the solar pumps not working on some days:*The median pump did not work for 122 of the 365 days in 2013. Recent spells of rainfall (in January, August and October) or lack of demand for water for reasons such asland being fallow in the lean season (in April, May and June) were the most common reasons for a pump not working in a dayacross different months (Figure 3). Technicalfaults with the solar array and power supply system were rare. Problems with the submersible pump and water distribution system were more common and inherited from the old PTW system. Our data, however, show that such faults were almost always remedied within a day with small outlay of a few hundred rupees. The money for repair was paid by the secretary of WUA from the irrigation revenue collected from farmers.

Figure 3 - Average number of days solar pumps did not work in different months in 2013



Source: Primary data collected by authors in Nalanda, Bihar.

3.2.Impact of affordable irrigation on wheat cultivation

Wheat was the most common crop grown by farmers in our sample in the *Rabi* season of 2012-13. 198 of the 240 farmers in our sample (138 treatment farmers and 60 control farmers) grew wheat in one of their plots. We collected data on inputs used in the wheat crop and output realized for 354 parcels of land operated by these 198 farmers. Of these 354 parcels, 206 were irrigated by solar pumps. Of the remaining 148 plots, 60 belonged to farmers who did not have access to irrigation from solar pumps on any one of their land parcels while 88 plots where of farmers who had some of their land irrigated by solar pumps.

203 of the 206 plots in the command area of solar pumps were irrigated exclusively by solar pumps. They did not require supplementary irrigation from diesel pumps as the solar pump could provide timely and adequate irrigation to almost all plots. The total cost of irrigation of wheat in these plots was Rs 813 per hectare of land. In comparison, the average cost of irrigation for plots irrigated solely by diesel pumps was nearly four times higher at Rs 3130 per hectare. It is interesting that even on plots that had access to affordable irrigation from solar pumps, farmers gave only two irrigations to their wheat crop. ThePTWs, unfortunately, do not have flow meters, so, we cannot estimate the total volume of irrigation water applied to the crop. The discharge rate of solar pumps shows significant variation across seasons and even within a day, so, we cannot provide even a rough estimate of the volume of irrigation applied, using hours of watering data. Plots irrigated with diesel pumps used 25 to30 hours of irrigation per hectare per watering.

Though plots irrigated by solar pumps received only two irrigations, the crop yield on these plots was 3.2 quintals per hectare (nearly 11 per cent) higher than the plots irrigated by diesel pumps (see table 1for regression results). This difference in yield remains even after we control for farmer's land holding size, soil quality of the plots, ownership of alternate sources of irrigation, application of NPK fertilizers, use of hired labor and village, and caste dummies. Since we make comparisons between solar and diesel pump irrigated parcels of the same farmer, we also effectively control for farmer's unobserved characteristics or endowments that may affect his crop productivity.

Table 1 – Impact of solar pumps on wheat yield (kg/ha)

VARIABLES	(1) Nocontrols	(2) Withcontrols	(3) Withdummies	(4) Solarfarmersonly
Ifsolarplot (1: Yes)	405.2***	349.4***	370.7***	304.2***
	(82.07)	(80.87)	(80.16)	(91.01)
Landowned (ha)		39.47	-13.21	-77.68*
		(35.02)	(37.62)	(41.76)
Hiredlabor (Rs/ha)		0.0198	0.0196	0.0497***
		(0.0134)	(0.0130)	(0.0170)
Urea(kg/ha)		0.893***	0.677***	1.188***
		(0.231)	(0.220)	(0.291)
DAP (kg/ha)		0.158	0.730***	0.777***
		(0.292)	(0.281)	(0.280)
Potash(kg/ha)		2.300	5.010***	4.205***
		(1.452)	(1.531)	(1.589)
Ifownsadieselpump (1: Yes)		80.50	97.60	175.7
		(84.03)	(98.80)	(110.6)
Constant	2,546***	2,068***	2,452***	2,001***
	(62.61)	(111.7)	(378.6)	(498.4)
Observations	354	354	354	294
R-squared	0.065	0.136	0.341	0.424
Village Dummy	NO	NO	YES	YES
Caste Dummy	NO	NO	YES	YES

Dependent Variable = Wheat Yield (kg/ha)
Standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Note: kg/ha=kilograms per hectare; Rs/ha=rupees per hectare

Source: Primary data collected by authors in Nalanda, Bihar.

Our data show that a farmer who has access to affordable irrigation from solar PTWs saves Rs 2300 on irrigation of wheat and reaps 3-3.2 quintals more produce (equivalent to additional revenue of Rs 5500 from wheat and husk) per hectare of land. Thus, his net profit from wheat is higher by about Rs 7500 per hectare compared to a similar farmer who depends exclusively on irrigation from diesel pumps. A typical solar powered PTW irrigated fivehectares of wheat crop in the *Rabi* season, thereby, creating total irrigation surplus of Rs37-38,000 in the season. It also saved 250-300 litres of subsidized diesel and reduced carbon emissions of 220-183 kg[6].

3.3. Impact of affordable irrigation on paddy cultivation

Nearly all farmers in Nalanda grow paddy in the monsoon season. Since, rainfall in the monsoon season was 25 per cent below normal in Nalanda in 2013 (IMD, 2015)**,** we decided to extend our survey to the *Kharif* season to see ifsolar pumps help in mitigating the impact of drought on paddy. We visited farmers we had surveyed in *Rabi* season two more times—once, at the time of sowing of paddy and a second time after paddy harvest, to collect data on inputs used and the output realized in the season. We have data from 239 farmers in our sample. All of them grew paddy in *Kharif*2013. One farmer (of 80), who did not have access to irrigation from a solar pump had left all his land fallow due to the drought.

Nursery preparation: In spite of the late onset of monsoon,all farmers sowed nursery on time in June. All of them, including those who had to incur a high cost of irrigation from own or rented diesel pumps, irrigated their nurseries to keep themstanding. Nurseries are small in size (roughly 4-5 per cent of the planned crop area) and therefore most farmers could afford to irrigate their nurseries. 146 of the 160 farmers with land in command area of solar pumps irrigated their nurseries with the solar pump itself. 14 of them chose to have nursery in land parcels closer to their home where solar powered irrigation was not available and used diesel pumps for irrigating their nurseries. Farmers watered their nurseries four to five times before transplantation. Few farmers who had their nurseries in the command area of solar pumpsused diesel pumps to irrigate their nurseries. The average cost of irrigation of a paddy nursery meant for a onehectare of transplanted area was around Rs 63 when solar pump was used. In comparison, cost of irrigating a nursery with diesel pumps was nearly six times higher, at Rs 386 per hectare.

*Paddy transplantation:*In the command area of solar pumps, paddy was transplanted ontime in nearly the entire area. 132 of the 160 farmers in our sample told us that they had transplanted paddy ontime in their entire land irrigated by solar pumps. Transplantation was late or not done mainly in cases, where the farmer planned to grow another crop like mustard or rapeseed in the plot or if he had a summer crop (for instance,maize or vegetables) in the plot that was harvested late. Only eightof the 160 farmers told us that they could not transplant paddy in their parcels irrigated by solar pumps because of drought and lack of irrigation. Altogether, paddy had been transplanted ontime in93 per cent of land within the command area of solar pumps. In comparison, only 42 per cent of farmers’ land (118 of 280 hectares) outside the command area of solar pumps had been transplanted with paddy till late August. Late transplantation of paddy affects not only the yield of this crop, but also delays wheat crop and makes it difficult to cultivatea third crop in the summer season. Late sown wheat is affected by terminal heat, gives low yield, and responds poorly to additional inputs like water and fertilizers. Thus, affordable irrigation from solar pumps will not only help to increase the area and production of paddy, but also the productivity of the whole rice-wheat system which accounts for more than 80 per cent of gross cropped area in the state.

*Irrigation costs and yields:*Farmers in Bihar rely mainly on rainfall to grow paddy. Supplemental irrigation is provided only when there is a long dry spell. In*Kharif*2013, however, almost all farmers in our sample in Nalanda irrigated paddy because of scanty rainfall. All 140 farmers who grew paddy in *Kharif* 2013, irrigated withsolar pumps only in their parcels in the command area of solar tubewells. A typical farmer irrigated his land three to four times with solar pump in the season. Total irrigation cost per hectare was Rs 1540, while the median cost was Rs 1250 per hectare, where one watering was priced at Rs 400 per hectare. Farmers did not need to supplement solar power with diesel pump-sets. The sky was mostly clear during the long dry spells in the season and solar pumps were working full time. Pump operation data for 12 months of 2013 also shows that pumps were used most intensively during August and September (Figure1).

Land outside the command area of solar pumps was irrigated either exclusively by ownor rented-in diesel pump-sets (62 per cent) or with canals (34 per cent) and village water bodies called *ahars* (4 per cent), supplemented by diesel pumps. Farmers who relied exclusively on diesel pump-sets spent, on an average, Rs 4850 per hectare on irrigation of paddy while those who also got one or two irrigations from canal or *ahar* spent Rs 3400 per hectare. Farmers who did not own a diesel pump-set had to rent it and they spent even more on irrigation. They, however, under-irrigated their crop and reaped around 1.8 quintal per hectare lower yields.

The productivity of paddy, on average, was nine per cent (or 238 kilogram per hectare) higher on plots irrigated by solar pumps even after we control for soil type, soil quality, land ownership, diesel pump ownership, and village and caste dummies (Table 2).The difference in productivity of paddy on solar and non-solar pump irrigated plots is relatively small, in spite of a major drought, because farmers coped with drought by reducing area under paddy on non-solar irrigated parcels and then irrigating thereducedcropped area intensively to protect the crop from moisture stress. Thus, the drought had a small effect on productivity of paddy, but a much larger effect on total production for farmers who did not have access to irrigation from solar pumps.

Table 2 - Impact of solar pumps on paddy yield (kg/ha)

VARIABLES	(1) basic	(2) Withcontrols	(3) CasteVillageDummies	(4) OnlySolarFarmers
Ifsolarplot	275.5***	264.5**	225.8**	255.7**
	(103.8)	(102.7)	(88.42)	(99.96)
Landowned		84.61*	85.35*	68.47
		(45.20)	(44.25)	(48.41)
HiredLabor(Rs/ha)		-0.00700	-0.00736	-0.00854
		(0.00934)	(0.00822)	(0.00853)
Urea(kg/ha)		1.987***	2.455***	2.537***
		(0.349)	(0.305)	(0.315)
DAP(kg/ha)		1.167	1.170	1.316
		(1.045)	(0.949)	(1.012)
Potash(kg/ha)		6.144*	9.389***	10.28**
		(3.663)	(3.168)	(4.304)
ifownsadieselpump		333.7***	208.4*	145.2
		(109.5)	(109.6)	(120.8)
Constant	3,379***	2,145***	1,124**	1,319**
	(81.83)	(224.1)	(439.2)	(527.3)
Observations	494	493	493	427
R-squared	0.014	0.100	0.411	0.423
Village Dummy	NO	NO	YES	YES
Caste Dummy	NO	NO	YES	YES

Dependent Variable = Paddy Yield (kg/ha)
Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Note: kg/ha=kilograms per hectare; Rs/ha=rupees per hectare

Source: Primary data collected by authors in Nalanda, Bihar.

To recap, access to irrigation from solar pumps had three major benefits for farmers in the *Kharif* season. First, farmers saved more than Rs 5200 per hectare in irrigation expenses. Second, farmers could grow crops on all their land in the command area of solar pumps, while they had to leave nearly one-third of their non-solar irrigated land fallow. Third, farmers were able to transplant paddy ontime in parcels irrigated by solar pumps, while transplantation was significantly late on other parcels of land. Timely sowing and transplantation of paddy in *Kharif* season would allow farmersto be on time for wheat sowing too. Fourth, productivity and production of paddy was higher where irrigation from solar pumps was available. Our estimates suggest that paddy grown on plots with solar irrigation generatedhigher net returns of Rs 8000 per hectare (Rs 5000 saved in irrigation cost + Rs 2800 from higher yield of 2.38 quintals),compared to plots irrigated exclusively by diesel pump-sets. Solar pumps would probably have a smaller impact on productivity, production and profits in *Kharif* season if the monsoon rainfall is timely and adequate.

3.4.Summer croppingwith solar pumps

Summer crops are rarely grown in Bihar. High cost of irrigation with diesel pumps is one of the reasons why farmers do not grow summer crops in the state. However, even farmers who gained access to cheap and abundant irrigation from solar powered pumps brought only six per cent of their land under summer crops. The other 94 per cent of cultivable land remained fallow in this season. In comparison, less than two per cent of area was brought under summer crops in parcels where farmers relied on diesel pump for irrigation. Thus, availability of affordable irrigation from solar pumps led to only a marginal increase in area under summer crops in among the farmers in our sample.

Farmers told us that starting cultivation of summer crops would require adjustments in their crop cycle: both paddy and wheat need to be sown and harvested earlier than usual to allow a third crop between wheat and paddy. Theysaid that they intended to make these adjustments from the next year. Area under summer crops is likely to increase substantially in the command area of solar pumps in years to come. Increase in area under summer crops will lead to a significant increase in farmers' income and it will also generate additional employment for men and women in agriculture.

4. Conclusion and policy implications

We tracked the performance of 16 solar powered PTWs in Bihar for a year in 2013 in Nalanda district of Bihar, using crop input and output data from 160 of the nearly 600 farmers who benefited from affordable irrigation from these pumps. For comparison, we also collected similar data from 80 farmers who had land close to, but outside, the command area of solar pumps. We visited these farmers five times during the year to collect high quality recall data. During each visit, we also collected data on pumps' operation and use from written records maintained by the operators of these community tubewells.

Our study shows that solar powered pumps are easy to use and manage, and work well in all seasons of the year. In the 12 months of 2013, very few incidences of fault were reported in the PV module, which were fixed soon with an average expense of less than Rs 1500. Most of the reported faults occurred in the electric pump and the water distribution system—both legacy issues from inefficient PTWs in Bihar.

Our data also show that access to affordable irrigation from solar pumps led to a nine to ten per cent increase in yields of both rice and wheat and a bigger increase in net income of farmers due to reduction in cost of irrigation. Solar pumps were also effective in mitigating the impact of a severe drought on *Kharif* crops. Paddy was transplanted in the entire command area of solar pumps, while nearly 40 per centof cultivable land outside solar pumps' command area was left fallow due to severe shortfall in monsoon rains.

It is our surmise that solar pumpswill have a bigger impact on productivity of the dominant rice-wheat cropping system and area under summer crops in subsequent years, once farmers adjust their crop cycle to the improved access to affordable irrigation. Solar pumps will encourage farmers to transplant and harvest paddy in time. This would permit timely sowing of wheat, which will in turn allow growing a third crop between wheat and paddy. That said, solar pumps will play a less important role in the *Kharif* season in years when rainfall is normal and timely.

We find that theincentives, the institutional model, and the technical design governing water distribution from the solar pumps,were limiting the efficiency and the impact of the solar powered irrigation systems that we study in Nalanda, Bihar.For example, all 16 tubewell operators in our sample told us that would be able to irrigate a significantly larger area if the tubewells were provided with longer and better piped distribution system. Some also suspected that the old pumps were inefficient. Yet, under the prevailing institutional arrangement, operators may not have the incentive to invest their own money in replacing the pump or extending the distribution system.

The MID installed PV systems on these PTWs with its own resources; beneficiary farmers did not contribute to the capital cost of the solarization. The MID also set the irrigation fee at Rs320-400 per irrigation per hectare, which is equivalent to an average volumetric price of Rs 0.2-0.25 per cubic metre. This is too low a water price. With such low prices, the tubewell barely generates enough to pay the operator’s wage and the system’s maintenance. If allowed to charge a higher irrigation fee, the WUA will be able to generate resources to extend the effective command area benefiting many more farmers with affordable irrigation. The WUA will also be able to set money aside for major repairs and eventual replacement of the pump and the panels, making itself more independent of the public support, and making the tubewells system more sustainable.

Solar pumps have high capital cost and small operating cost. Such highly leveraged investments become financially viable only with high capacity utilization. At present, an average solar pump runs for only 900-1000 hours a year, eventhough it gets enough radiation that it can run for twice as long. Hadthe WUAs managing the solar powered tubewells in Nalanda borrowed even a part of the capital cost of the solar arrays, they would be under pressure to run the pump whenever sun light was available to generate revenue to pay their instalments and interest. Similar pressure felt by electric tubewell owners in the neighbouring state of West Bengal dueto high flat electricity charges, intensified competition among them and created a buyers' irrigation service market in which, tubewell owners provided high quality irrigation service at very competitive prices (Mukherji, 2007a; Mukherji, 2007b). For water-abundant, especially flood-prone areas of Bihar and neighboring regions in the lower Gangetic basin (such as Eastern Uttar Pradesh, West Bengal, Bangladesh, and Nepal Terai), solar irrigation pumps can prove to be a godsend technology, especially for credit constrained smallholders.

Government of Bihar is still building3000 new PTWs, under an ongoing 27 million USD project funded by the Rural Infrastructure Development Fund (RIDF) (MWRD, 2015). These tubewells will be powered by DGs. Our experience from the field government’s own audits show that tubewells with DGs do not work, as rural power supply is still quite poor in Bihar. Our study of

16 solar powered public tubewells in Nalanda suggests that equipping defunct community tubewells with solar arrays may be an effective approach to rehabilitating them. Therefore, we recommend that all new PTWs be equipped with solar power. Government should, however, allow the WUA to decide the water price instead of fixing it at the current low levels. The WUA would not be able to charge predatory prices as it will face competition from diesel pump-sets. The government should also collect a fixed monthly rent from the WUAs in lieu of its capital investment in solarized PTWs. The fixed monthly rent will not only cover part of the capital cost of the system, but also force tubewell operators to aggressively expand command area and serve more farmers. This will improve the economic viability and impact of solar pumps.

Acknowledgments

Authors would like to thank the Indian Council of Agricultural Research (ICAR) and Climate Change, Agriculture and Food Security (CCAFS) program, for partially supporting this research. We also thank the farmers in Nalanda, whom we visited repeatedly over a period of one year, for their time and for educating us on the irrigation practices in the region. Claro Energy, a start- up solar power company, helped us in reaching farmers who were using solar pumps in Bihar. Any errors in the paper are our own.

---

[1] State governments of Bihar, Rajasthan, Gujarat, Karnataka, Tamil Nadu, and Punjab, among others have initiated schemes for solar powered irrigation.

[2] Electricity from solar supplied to the grid has fallen to just 8.78 rupees per kilowatt-hour compared with 17 rupees for diesel (Pearson, 2012)

[3] Most parts of India receive daily solar incidence between 5.4 to 5.8 kWh/m^2(See Figure 2 in Sharma et al., 2012).

---

[4] Price of solar panels has declined rapidly from \$22 per watt power in 1980 to only 67 cents per watt power in 2014 and most analysts agree that solar panels will become still cheaper in the future, making solar energy an increasingly cost-effective option in future (Naam, 2011).

[5] *Katha* is the local unit of area in Bihar. In Nalanda district, 32 *katha* form an acre of land.

[6] One liter of diesel emits around 0.732 kg of carbon (Nelson and Robertson (2008) cited in Shah (2009)).

References

Ballabh, V., 1987. Decline of a novel experiment: A case study of group irrigation tubewells in Deoria District. Anand: Institute of Rural Management, unpublished report.

Burney J., Woltering, L., Burke, M., Naylor R., Pasternak, D., 2010. Solar-powered drip irrigation enhances food security in the Sudano–Sahel. Proceedings of the National Academy of Sciences of the United States of America. 107(5), 1848–1853.

GIZ, 2013. Solar water pumping for irrigation: Opportunities in Bihar, India. New Delhi:GIZ.

IMD (Indian Meteorological Department), Government of India , 2015. http://www.imd.gov.in/section/hydro/distrainfall/webrain/bihar/nalanda.txt.[Accessed 18th February, 2015].

Kelley, L.C., Gilbertson, E., Sheikh, A., Eppinger, S.D., Dubowsky,S., 2010. On the feasibility of solar-powered irrigation. Renewable and Sustainable Energy Reviews.14, 2669–2682

Kolhe, M., Kolhe, S., Joshi, J., 2002. Economic Viability of Stand-alone Solar Photovoltaic System in Comparison with Diesel-Powered System for India. Energy Economics. 24, 155–165.

Kumar, A., Kandpal C.T., 2007. Potential and cost of CO_2 emissions mitigation by using solar photovoltaic pumps in India. International Journal of Sustainable Energy. 26(3), 159-166, DOI: 10.1080/14786450701679332.

Meah, K., Ula, S., Barrett, S., 2008. Solar photovoltaic water pumping — opportunities. Renewable and Sustainable Energy Reviews. 12, 1162–1175.

MNRE (Ministry of New and Renewable energy), Government of India, 2015. http://mnre.gov.in/file-manager/offgrid-solar-schemes/NABARD-operational-Guidelines-of-Solar-Water-Pumping-Programme.pdf [Accessed 18th February, 2015].

MWRD (Minor Water Resources Department), Government of Bihar, 2015. http://mwrd.bih.nic.in/On%20Going%20Schemes.htm[Accessed 18th February, 2015].

Mukherji, A., 2007a. The energy-irrigation nexus and its impact on groundwater markets in Eastern Indo-Gangetic basin: Evidence from West Bengal, India. Energy Policy, 35(12): 6413-6430.

Mukherji, A., 2007b. Implications of alternative institutional arrangements in groundwater sharing: Evidence from West Bengal. Economic and Political Weekly. 42(26), 2543-2551.

Naam, R., 2011. Smaller, Cheaper, and Faster: Does Moore’s Law Apply to Solar Cells. Scientific American, 16 March.

Odeh I.,Yohanis Y.G., Norton, B., 2006. Economic Viability of Photovoltaic Water Pumping Systems. Solar Energy. 80, 850–860.

Pant, N., 1984. Community tubewell: An organizational alternative to small farmers' irrigation. Economic and Political Weekly. 19(26), 59-66.

Pearson, N.M, 2012. Solar Cheaper Than Diesel Making India's Mittal Believer: Energy. Bloomberg, http://www.bloomberg.com/news/articles/2012-01-25/solar-cheaper-than-diesel-making-india-s-mittal-believer-energy [Accessed 19th February, 2015].

Ramos, J.S., Ramos, H.M., 2009.Solar powered pumps to supply water for rural or isolated zones: A case study.Energy for Sustainable Development.13, 151–158.

Shah, T., 2007. Crop per Drop of Diesel? Energy Squeeze on India's Smallholder Irrigation. Economic and Political Weekly. 42(39), 4002-4009.

Shah, T., 2009. Climate change and groundwater: India's opportunities for mitigation and adaptation. Environmental Research Letters. 4, 035005.

Shah, T., Kishore, A., 2012. Solar-Powered Pump Irrigation and India's Groundwater Economy: A Preliminary Discussion of Opportunities and Threats, Anand: International Water Management Institute.

Sharma N., A., 2005. Agrarian Relations and Socio-Economic Change in Bihar. Economic and Political Weekly. 40(10), 960–972.

Sharma, N.K., Tiwari, P.K., Sood Y.R., 2012. Solar energy in India: Strategies, policies, perspectives and future potential.Renewable and Sustainable Energy Reviews.16, 933-941.

World Bank, 2015. http://www.worldbank.org/en/news/press-release/2013/09/30/project-signing-10-million-grant-for-solar-irrigation-in-bangladesh [Accessed 13th February, 2015].