Solar irrigation in Nepal: Equity in energy access and implications for fossil fuel use

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Abstract

In Nepal, solar irrigation is being promoted by federal and local governments to supply individual subsidized pumps to poor and marginalized farmers, and to reduce the use of fossil fuels in irrigation. Using data from a primary survey of 656 farming households in rural Nepal, we investigate whether solar irrigation is indeed pro-poor and if it does reduce fossil fuel use. We find that subsidized solar pumps were more likely to be owned by households of higher social status and greater wealth. We also find that although solar-pump users continued to also use fossil-fuel pumps, they operated their fossil-fuel pumps for fewer hours than those who did not have solar pumps, especially during the rainy season. These results suggest that in the Nepali *terai*, solar pumps benefit socioeconomically advantaged farmers and only marginally reduce fossil fuel use.

Key words: *solar irrigation, equity, social capital, fossil fuel use*

1. Introduction

Groundwater is important for irrigation in South Asia (Agrawal and Jain, 2019; Shah et al., 2004, 2001); 60% of the estimated 90 million hectares of farmland that are irrigated there is supplied by groundwater (Frenken, 2012). With changes in monsoon patterns due to climate change, reliance on groundwater for irrigation will likely increase, especially for small and marginal farmers (Khan et al., 2013; Turral et al., 2011).

Solar-powered irrigation is a promising technology that improves smallholders' access to agricultural water without using fossil fuels. There are several factors that make solar irrigation attractive. From the farmer's perspective, there are no fuel costs and maintenance costs are low (Kelley et al., 2010). From the government's perspective, offering a one-time subsidy to reduce the (high) upfront purchase costs for farmers is less fiscally burdensome than perpetual subsidies on electricity (Rathore et al., 2018). Whether the goal is to provide cost-effective energy to smallholders in order to expand agricultural production and productivity (e.g. in Nepal and Bangladesh; (Foster et al., 2021; Mukherji, 2007; Urfels et al., 2020), or to reduce the burden of fuel subsidies (e.g. in India and Pakistan; (IRENA, 2016)), solar irrigation pumps (SIPs) are an important technology for the agricultural sector, and early assessments show positive impacts on cropping area, cropping intensity, and incomes (Gupta, 2019; Kishore et al., 2017).

SIPs are being subsidized by various governments across South Asia (Closas and Rap, 2017). For example, since 2010, the state of Rajasthan in India has offered subsidies of 60-86% for purchasing individual SIPs (Gupta, 2019). In Bangladesh, solar irrigation entrepreneurs receive a subsidy of 50% to set up community SIPs that serve small command areas of 30-50 acres (Mitra et al., 2021; Vivid Economics, 2019). Nepal is providing a 60% subsidy on individual SIPs to smallholder households in the terai regions, as is the Indian state of Bihar (Bastakoti et al., 2019).

Two important claims are made in the literature about solar irrigation. The first is related to carbon emissions (Bassi, 2018), with SIPs viewed as a way of replacing fossil fuel energy with clean energy, thus helping countries meet emission reduction goals and targets (Agrawal and Jain, 2019; Gupta, 2019; Joshi et al., 2019; Kishore et al., 2014; Kumar and Kandpal, 2007; Lefore et al., 2021; Rathore et al., 2018). The second is that solar irrigation is pro-poor; SIPs can supply energy to meet the needs of small and marginal agricultural households (Kishore et al., 2017; Shah et al., 2014). It is unclear to what extent either of these claims is true (Lefore et al., 2021; Sharma, 2021).

In developing countries where energy use for irrigation in the agricultural sector is low to begin with, solar energy might expand total energy use without necessarily replacing fossil fuels (Bhandari and Stadler, 2011). Depending on their capacity, SIPs may supplement fossil fuel pumps in irrigating farm lands (Sharma, 2021). Further, SIPs may not replace fossil fuel pumps in environments where markets for pump lending exist (such as in Bangladesh, West Bengal and the Nepal terai; see (Buisson et al., 2021; Mottaleb et al., 2019; Mukherji, 2007); the immobility of SIPs makes renting them out to marginal farmers difficult. This immobility also affects the degree to which SIPs are pro-poor. Given that marginal farmers tend to have more fragmented and non-contiguous land holdings, the mobility of fossil fuel pumps may serve them better (Sharma, 2021). In addition, there is emerging evidence that certain groups based on social identities (caste, tribe, ethnicity, networks), gender and wealth are more likely to be excluded from solar irrigation programs (Lefore et al., 2021), but cases studies are few.

We use the case of the *terai* region in Nepal to examine whether individual SIPs reduce fossil fuel use. Farmers in this region have received subsidized solar pumps from the Alternative Energy Promotion Center (AEPC), the Government of Nepal's nodal agency for promoting and facilitating use of alternative energy, including SIPs. The conditions in the *terai*, however, may not be favorable for fossil fuel reduction. Agriculture across Nepal accounted for less than 1% of total energy consumption in 2005 (Bhandari and Stadler, 2011), and despite plentiful shallow groundwater, farmers in the *terai* tend to not irrigate crops fully due to high diesel prices (Foster et al., 2021; Urfels et al., 2020). This underutilization of energy, combined with the presence of fragmented land holdings in the region, suggest that solar pumps may not necessarily reduce fossil fuel use in the Nepali *terai*.

We also examine whether solar irrigation is pro-poor in Nepal. This question is motivated by the process through which the federal government selects households for receiving SIPs. AEPC makes periodic calls for applications through radio, television and newspapers; and firms that specialize in installing SIPs collect and submit applications prepared by the farmers along with the required letters of support from the local government offices (in conversation with program staff at AEPC). Given that this process takes place against the backdrop of Nepal's complex (and rigid) structure of social identities that are based on caste, ethnicity and religion (Desai and Dubey, 2012), and where access to goods and services offered by public and private institutions is mediated by these identifies (e.g. see Balasubramanya et al. 2021); the possibility of elite capture (Shrestha et al., 2020) of solar irrigation in Nepal is reasonably high.

To examine whether solar irrigation is pro-poor, we distinguish between recipient households (applied for a SIP and were granted one), applicant households (applied for a SIP but were not granted one), and non-applicant households (have yet to apply for a SIP). To examine whether solar irrigation reduces fossil fuel use, we distinguish between households that are SIP users (in this case, all households owning SIPs were also users; they might also use fuel pumps); and fuel-pump users (households that do not own or use SIPs but used only electric or diesel pumps for irrigation).

Results show that SIP recipient households are from elite social groups, are better connected socially, and are wealthier (greater land size, higher income) than applicant and non-applicant households. In addition, most SIP users also employed fuel pumps for extracting water for irrigation, aquaculture, or livestock; however, SIP users reported operating fuel pumps for fewer hours than fuel-pump users, especially in the rainy season. Finally, SIP users were more likely to report practicing water-intensive activities such as aquaculture than fuel-pump users. These results suggest that solar irrigation in the *terai* has largely benefitted households from elite social groups and has likely decreased fossil fuel use marginally.

The rest of the paper proceeds as follows. In section 2, we provide a brief overview of solar irrigation in Nepal. Section 3 describes data, and methods are presented in section 4. Results are presented in section 5 and section 6 concludes.

2. Solar irrigation in Nepal

As part of its Nationally Determined Contributions commitment to the Paris Agreement, the Government of Nepal aims to generate more than 4,000 megawatts (MW) of renewable energy (solar energy, bio-energy, wind energy, and mini-hydro) by 2030 (Government of Nepal, 2020). In addition to providing fiscal support for homestead solar energy in rural areas, solar-powered irrigation has been embedded in the country's alternative energy plans and, as of 2021, the government has installed about 2,000 subsidized SIPs (AEPC, 2018)[1]. While requests to AEPC for SIPS have increased sharply, [2] the agency is unable to meet all requests due to limited financial resources; between 2016 and 2020, AEPC was able to meet only 21% of requests. The majority of SIPs deployed have been distributed to the *terai* region (see Figure 1), which is the breadbasket of the country due to its flat and fertile terrain and groundwater reserves (Adhikari et al., 2021; Urfels et al., 2020).

--Figure 1 here--

Solar pumping systems were first installed in Nepal in early 2006; and began expanding substantially in 2016 due to the Renewable Energy Subsidy Policy. In 2018, the federal government of Nepal allocated US$ 30 million for solar irrigation expansion, and tripled it in 2019 (Ministry of Finance, 2020). The government also empowered AEPC to serve as the nodal agency that both receives requests and deploys SIPs. AEPC works in conjunction with local

[1] Private and non-governmental organizations have also distributed a few hundred SIPs over the last few years (Mukherji et al., 2017).
[2] They received a record high of 4,600 applications in 2020 compared to 300 applications in 2017.

governments, and local levels of federal government agencies such as the agricultural extension services and the National Electricity Authority.

The AEPC's SIP program is attractive to farmers because it subsidizes 60% of the cost of individual SIPs, and offers a subsidy of NPR 2,000,000 (~USD 20,000) for community PV solar systems (AEPC, 2016). Through this program, the government aims to reduce fossil fuel use in agriculture and to enhance rural livelihoods, particularly of vulnerable households, that include but are not limited to single women, socially and economically disadvantaged groups, and ethnic minorities. Most local governments have integrated solar-irrigation development into their annual programs.

3. Data

Data used in this analysis come from a household and agriculture survey that was designed and implemented in 2021 by the authors. The survey covered 675 farming households (325 SIP users and 350 fuel-pump users) from 15 municipalities, seven districts and two provinces in the eastern *terai* region of Nepal. The sample size was determined using statistical power calculations ensuring 80% statistical power, 5% Type I error, and an intra-cluster correlation of 0.1. Power analysis was conducted using data from the 2011 Agricultural Census (Central Bureau of Statistics, 2013). While agricultural census data were available at the village development committee (VDC) level, it had to be aggregated to the district level because the country went through a major administrative reform in 2015.[3] Therefore, power calculations were based on district level data for the six districts from Province 1 and *Madhesh* Province.

[3] Some VDCs were merged, while others were split to form new administrative units.

The survey elicited information on household demographics, social networks, farm characteristics, crop production, water extraction mechanisms (and their repair and maintenance), livestock and aquaculture, income sources, and ownership of household and farm assets. The social network data included information on households' participation in different groups (community, production, water users etc.), their access to local and federal governments, and their relationships with local leaders and government officials.

The agricultural module elicited information on land area owned, cultivated area sharecropped or rented in, and the number of crops cultivated in the last three major agricultural seasons. Households were asked about the irrigation status, source of water for irrigation, and the type of water extraction mechanism used for each plot over the last three agricultural seasons. Information was also collected on irrigation service markets: whether the households rented irrigation pumps and pipes in or out during the last three agricultural seasons or purchased irrigation water from other households. Crop production details (input use, labor, irrigation, and harvest) for the last three agricultural seasons were also recorded, as was data on ownership of livestock and on aquaculture activities. Information on market access and sale of agricultural products was also recorded at the household level.

Finally, household wealth status was elicited by collecting data on household assets, agricultural assets, agricultural revenues, and non-agricultural incomes (both cash and in-kind). Asset data consists of household durables and housing quality characteristics. Data was available for 32 different items.[4] To deal with the extensive list of assets, we construct an aggregated asset

[4] Household durables include tables, chairs, sofas, bed or mattress, fan, heater, AC, sewing machine, Iron, refrigerator or freezer, stoves, electric/gas stove, radio/CD, TV/VCR/DVD, satellite dish, solar panel, generator, computer or laptop, bicycle, motorcycle, motor vehicle, boat. Housing quality characteristics include indicator for improved floor, improved roof, improved wall, cooking fuel, flush toilet, and access to electricity.

index using the principal component analysis. We use only the first principal component as weighted index because it serves as a good proxy for household socioeconomic status (Filmer and Pritchett, 2001).

4. Methods

We estimated the probability of receiving SIPs as a function of the household's social identity, social networks, and household wellbeing (assets, income etc.) using a probit estimator. Then, we explored the correlation between SIP use and the use of fuel pumps for agricultural water extraction, using probit regressions again. To account for farmer-level heterogeneity in the intensity of using different types of pumps, we estimated the relationship between SIP use and the hours of fuel- pump use using Ordinary Least Square (OLS) regression.

5. Results and discussion

5.1. Descriptive results

Table 1 presents summary statistics of key variables used in the analysis. The first column presents statistics for the full sample. Columns 2-4 present summary statistics for SIP recipients, SIP applicants (applied for a SIP but did not receive it), and SIP non-applicants (who never applied for a SIP.

The first panel in Table 1 reports statistics on water extraction mechanisms. With over two-thirds of farmers using them, diesel pumps were the most commonly used agricultural water extraction mechanism. Diesel pump use was highest for SIP applicants (79%); followed by SIP non-applicants (65%); however even among SIP recipients, 63% reported using them. Electric pumps were being used 39% of all households; 49% of SIP non-applicants, 39% of SIP applicants and 34% if Sip recipients used them. Nearly 20% of the full sample reported renting pumps from other households, and about 15% reported renting their pumps out to others. SIP applicants (27%) and SIP non-applicants (28%) were more likely to rent pumps in than SIP recipients (10%), whereas SIP recipients were more likely to rent their pumps out to others (19%) compared to SIP-applicants (15%) and SIP-non-applicants (7%).

The second panel of Table 1 reports statistics related to social identity. Around 60% of households in the sample were *Madheshi*, a community of Nepali citizens of Indian origin and the dominant community in the study area; they were equally represented among SIP recipients, SIP applicants and SIP non-applicants. Around 23% of the sample was *brahmin* or *chhetri* households, castes that have historically enjoyed social and economic advantage; while 23% of SIP recipients and 25% of SIP applicant households were *brahmin* or *chhetri;* only 18% of SIP non-applicant households belonged to these castes. Finally, while 17% of all households belonged to minority castes that have historically been deprived of social and economic advantage; these were not equally represented among the three groups; 22% of non-applicant households were from minority cases, while 17% and 15% of SIP-recipient and SIP-applicant households belonged to these castes.

The third panel of Table 1 reports household assets and income sources. The average household asset index for recipient households was 0.8 standard deviations greater than that for applicant households and was nearly 1.5 standard deviations greater than that for non-applicant households. Around 43% of households had at least one member that was wage employed, and 33% of households had at least one member that was self-employed. While 43% of households received cash transfers, these were not equally represented between the three groups; while 52% of recipient households received cash transfers, only 34% of applicant households and 39% of non-applicant households received such transfers.

Panel 4 in Table 1 reports statistics on agricultural activities. SIP recipient households had larger land holdings that applicant and non-applicant households; they also cultivated and irrigated a greater number of crops. Around 18% of SIP recipient households practices aquaculture, as compared to 9% of applicant households and 6% of non-applicant ones. Households keeping livestock were equally represented in all three groups.

Finally, around 45% of SIP-recipient households reported the most educated member in their household to have a college degree or above, as compared to28% of applicant households and 26% of non-applicant households (Table 1, panel 5), indicating that recipient households were more educated.

--Table 1 here--

Figure 2 illustrates the combinations of different pump types that households reported using concurrently. Just under half of all households used multiple pumps (22% solar and diesel; 9% solar and electric; 7% solar, diesel and electric; and 10% diesel and electric). Likely due to the lack of mobility of SIPs, only 18% of SIP users rely on their solar pumps alone. Nearly two thirds, however, supplement their solar powered pumps with diesel pumps (48% solar and diesel; and 15% solar, diesel and electric), and a quarter supplement them with electric pumps (19% solar and electric; and 15% solar, diesel and electric).

--Figure 2 here--

Table 2 provides additional details on water extraction mechanisms used by SIP users before and after installing SIP. The first panel in the table shows water extraction mechanism in SIP plots before installing SIPs. Before SIP, diesel pumps were the most commonly used water extraction mechanism (78%) followed by electric pumps (11%) and manual pumps (7%). The second panel in Table 2reports how SIP users handled previously used fuel pumps after switching to SIPs. About two-thirds of SIP users reported that they were still using their fuel pumps along with newly installed SIPs, either on the same plot (27%) or on a different plot than the one irrigated by the SIP (40%). While about 10% of SIP users reported selling their fuel pumps, about 12% of farmers who were renting fuel pumps from other farmers stopped doing so after receiving their own SIPs. Farmers were also asked to report their reasons for switching to SIPs (Panel 3, Table 2). Diesel prices was the most commonly reported reason (62%) but more than 19% of households cited erratic electricity supply as a reason for switching to SIPs. A large share of household found SIPs to be a cost-saving alternative, either due to zero-operating costs (45%) or because they incurred no expenses for procuring and installing them (38%).

--Table 2 here --

Table 3 reports social networks of households by SIP status. Recipient households s reported stronger social networks than applicant and non-applicant households, with recipient households more likely to have at least one family member participating in farmers' groups/cooperatives and in saving/micro-finance groups. Over 90% of recipient households reported having family members who held government positions in the Ward level, and over 80% reported having family members who held government positions in the municipality level. Similarly, 87% of applicant households reported having family members who held positions in the Ward level and 70% reported having family members who help positions in the municipality level. Although the percentages are still high, a smaller percentage of non-applicant households reported having family members in Ward and municipality government (73% and 51%, respectively). This access to local government is associated with recipient households also reporting greater ease of approaching local government offices as compared to applicant and non-applicant households.

--Table 3 here—

5.2. Correlates of receiving SIP

Table 4 presents probit estimates of the relationships between receiving SIPs and households' social networks, social identities, and household assets and income. Column 1. Households with better social networks were more likely to have received SIPs, *ceteris paribus*, especially those with connections to the government (top panel, Table 4). Farming households with at least one member in a farmers' group were 8% more likely to have received SIPs than those who did not have any members in farmers' groups. Likewise, households that had a member in a saving or micro-finance group were 7% more likely to receive SIPs than those who did not. Importantly, households that had at least one member employed by the local or federal government were 15% more likely to have received SIPs than those without such a connection.

While social identity was not correlated with receiving a SIP, households with higher asset wealth and those that received government transfers were more likely to be SIP recipients (bottom panel, Table 4). Farming households in the bottom 40th percentile of the household asset index distribution were15% less likely to have SIPs than those in the top 20th percentile. Households in the middle 40th percentile of the household asset distribution were also less likely to receive SIPs than those in the top 20th percentile, but the relationship was not statistically significant. Although the types of household labor income sources (e.g. wage employment or self-employment) were not statistically correlated with receiving SIPs, households that received cash or in-kind transfer from the government were 19% more likely to have received them.

--Table 4 here—

5.3. Correlates of fuel pump use

Table 5 presents the probability of using fuel (diesel and electric) pumps for agricultural water extraction, given the status of SIP program participation. Results show that, compared to the farmers who never applied to the SIP program, those who received SIPs were 4% less likely to use diesel pumps (though statistically not significant) and 19% less likely to use electric pumps. Farmers who applied for SIP but did not receive the pump were 9% more likely to use diesel pumps but 8% less likely to use electric pumps. The second panel in Table 5 shows the relationship between farmers' social networks and the use of non-solar pumps. Even though the probability of receiving (and using) solar pumps is positively correlated with social networks (see Table 4), the probability of using diesel or electric pumps is not correlated with social networks.

Social identity of farmers, however, is correlated with the use of diesel and electric pumps. Compared to *Madheshi*, the majority social group in the region, *Brahmin/Chhetri*, and *Janajati* are less likely to use diesel pumps but more likely to use electric pumps. The relationship is exactly opposite for *Muslim* farmers; they are 15% more likely to use diesel pumps and 19% less likely to use electric pumps than *Madheshi* farmers.

--Table 5 here--

The final panel in Table 5 presents the relationship between household wealth status (assets and income) and use of fuel pumps. Compared to farmers in the top 20th percentile of household asset distribution, farmers in the bottom and middle 40th percentile are 10% less likely to use diesel pumps. Farming households that have at least one family member employed in wage earning activities are about 9% less likely to use diesel pumps than those without a wage-employed family member. The relationship between household wealth (asset and income) indicators and electric pump use is also negative, but it is not statistically significant. Households that received cash or in-kind transfers from the government are 8% more likely to use electric pumps and 2% less likely to use diesel pumps, although the latter is not statistically significant.

5.4. Intensity of using fuel pumps

Table 6 presents the relationship between SIP program participation and the intensity of using diesel or electric pumps in different agricultural seasons. Results in the first panel show that farmers who received SIPs use less hours of fuel pumps than those who never applied to the program. The relationship persists in both rainy and dry seasons, but the magnitude of effect is greater in rainy season than in dry season. In rainy season, SIP recipients use 16 less hours of diesel pumps and one less hour of electric pumps than those who never applied for SIPs; in dry season, they use 11 less hours of diesel pumps. SIP applicants (farmers who applied for SIPs but did not receive the pumps) also use less hours of diesel pumps than those who never applied for SIP, though not statistically significant. These farmers used more hours of electric pumps in both seasons than those who never applied for SIP, but none of these changes is statistically significant.

--Table 6 here—

The second panel of Table 6 presents the relationship between the intensity of fuel pump use and social networks. Households that held membership in farmers' groups use 8 more hours of diesel pumps and 14 more hours of electric pumps than those who did not held such membership. Households that had one or more members working in a government office also used more hours of fuel pumps in rainy season, but their use of fuel pumps is not statistically significantly different from those who did not hold any government position.

6. Conclusion

In an era of frequent and intense climate change events, solar irrigation is being promoted by policymakers and development stakeholders as both climate mitigation and adaptation strategy, especially to supply individual subsidized pumps to poor and marginalized farmers, and to reduce the use of fossil fuels in irrigation. We studied Nepal's solar irrigation program to examine whether the program is pro-poor and whether the use of solar pumps reduces fossil fuel use. We use the Government of Nepal's solar irrigation program rollout and categorize farmers to three distinct groups; recipient households (applied for a SIP and were granted one), applicant households (applied for a SIP but were not granted one), and non-applicant households (have yet to apply for a SIP). We use data from a primary survey of 656 farming households in Nepal's *terai* region where the solar program is concentrated.

We find that farmers belonging to elite social groups, those with better social connection, and wealthier farmers (greater land size, higher income) were more likely to receive SIPs than farmers with poor social connection or lower socioeconomic status. We also find evidence that most farmers who received SIPs also used fuel or electric pumps for agricultural water extraction. Farmers who received SIPs, however, used diesel pumps for fewer hours than fuel-pump users.

These results suggest that Nepal's solar irrigation program (mostly concentrated in the *terai* region) has largely benefitted relatively well-off farmers (those belonging to elite social groups and with high socioeconomic status) and the program may have decreased fossil fuel use only marginally. The absence of significant reduction in fossil fuel use is not surprising because the conditions in the *terai* region may not be favorable for fossil fuel reduction. Agriculture across Nepal accounted for less than 1% of total energy consumption in 2005 (Bhandari and Stadler, 2011), and despite plentiful shallow groundwater, farmers in the region tend to not irrigate crops fully due to high diesel prices (Foster et al., 2021; Urfels et al., 2020). This underutilization of energy, combined with the presence of fragmented land holdings in the region, suggest that solar pumps may not necessarily reduce fossil fuel use in the Nepali *terai*.

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Tables and Figures

Table 1. Descriptive statistics of key variables by solar irrigation pump application status

Variables	Full sample	SIP users	*Fuel pump users* SIP applicants (applied but not received)	*Fuel pump users* SIP non-applicants (never applied)
	(1)	*(2)*	*(3)*	*(4)*
Water extraction mechanism				
Used diesel pumps	0.68	0.63	0.79	0.65
	(0.097)	(0.105)	(0.127)	(0.083)
Used electric pumps	0.39	0.34	0.39	0.49
	(0.097)	(0.092)	(0.135)	(0.101)
Rented others' pumps/pipes	0.19	0.10	0.28	0.27
	(0.049)	(0.041)	(0.084)	(0.053)
Rented pumps/pipes to others	0.15	0.19	0.15	0.074
	(0.053)	(0.066)	(0.065)	(0.043)
Social identity				
Madheshi	0.59	0.59	0.60	0.60
	(0.106)	(0.122)	(0.131)	(0.095)
Brahmin/Chhetri	0.23	0.23	0.25	0.18
	(0.106)	(0.116)	(0.132)	(0.104)
Minorities (*tharu*, muslim, *dalit*, *janajati* etc.)	0.17	0.17	0.15	0.22
	(0.039)	(0.057)	(0.044)	(0.047)
Assets and Income				
Household asset index	0.00	0.57	-0.21	-0.89
	(0.383)	(0.451)	(0.455)	(0.370)
At least one member is wage-employed	0.43	0.43	0.43	0.46
	(0.019)	(0.033)	(0.026)	(0.027)
At least one member is self-employed	0.33	0.35	0.33	0.29
	(0.034)	(0.045)	(0.060)	(0.052)
Household received cash transfers	0.43	0.52	0.34	0.39
	(0.025)	(0.039)	(0.041)	(0.073)
Agriculture				
Land area owned (acre)	1.90	2.34	1.78	1.16
	(0.193)	(0.348)	(0.206)	(0.151)
Number of crops cultivated	3.25	3.31	3.21	3.18
	(0.143)	(0.171)	(0.137)	(0.234)
Number of irrigated crops	2.73	2.77	2.69	2.73
	(0.114)	(0.106)	(0.131)	(0.251)
Aquaculture	0.13	0.18	0.093	0.061
	(0.040)	(0.060)	(0.037)	(0.032)
Kept livestock	0.88	0.88	0.86	0.88
	(0.031)	(0.032)	(0.040)	(0.050)
Household characteristics				
Household size	7.72	7.81	8.10	7.07

	(0.519)	(0.466)	(0.830)	(0.657)
Head's gender (1=Female, 0=Male)	0.94	0.93	0.94	0.96
	(0.017)	(0.017)	(0.021)	(0.019)
At least one member is a migrant	0.31	0.31	0.25	0.38
	(0.037)	(0.048)	(0.052)	(0.054)
Highest level of education				
Lower secondary (1-8)	0.073	0.059	0.049	0.13
	(0.018)	(0.019)	(0.021)	(0.049)
Secondary (9-12)	0.57	0.49	0.66	0.61
	(0.023)	(0.035)	(0.037)	(0.054)
College or above	0.35	0.45	0.28	0.26
	(0.024)	(0.040)	(0.027)	(0.040)
Number of households	**656**	**303**	**205**	**148**

Notes: Point estimates are means. Standard errors are in the parentheses.

Table 2. Water extraction mechanisms before and after installing solar irrigation pumps (SIP users only)

Variables	Mean *(1)*	Std. error *(2)*
What was the water extraction mechanism on this plot before installing SIP?		
1. Diesel pump	0.780	0.052
2. Electric pump	0.115	0.043
3. Manual pump	0.066	0.019
4. No irrigation	0.036	0.016
What did you do with the previously used fuel pump after switching to SIP?		
1. Moved to another plot	0.395	0.087
2. Still in use on the same plot	0.266	0.070
1. Sold	0.102	0.077
2. Stopped renting pump	0.122	0.039
3. Don't know/No response	0.115	0.026
Why did you switch to SIP?		
1. Diesel prices too high	0.625	0.075
2. Unstable electricity supply	0.191	0.039
3. Zero operating cost for SIP	0.447	0.063
4. Received SIP free of cost	0.385	0.059
Did you change the types of crops after switching to SIP? (1=Yes, 0=No)	0.438	0.096
Number of households	**304**	

Notes: Point estimates in column 1 are means. Standard errors are in column 2.

Table 3. Social networks and SIP use

Social network variables	Full sample	SIP users	*Fuel pump users* SIP applicants (applied but not received)	SIP non-applicants (never applied)
	1	*2*	*3*	*4*
At least one family member was a member of…(1=Yes, 0=No)				
Farmers' group/cooperative	0.43	0.49	0.42	0.32
	(0.057)	(0.049)	(0.087)	(0.091)
Saving/micro-finance group	0.41	0.44	0.37	0.41
	(0.031)	(0.048)	(0.040)	(0.042)
Family member(s) held position in the government (1=Yes, 0=No)				
Ward	0.86	0.92	0.87	0.73
	(0.022)	(0.023)	(0.030)	(0.039)
Municipality	0.71	0.81	0.69	0.51
	(0.059)	(0.070)	(0.067)	(0.059)
District, Province, or Federal	0.19	0.25	0.18	0.11
	(0.058)	(0.066)	(0.071)	(0.048)
Number of households	**656**	**303**	**205**	**148**

Notes: Point estimates are means. Standard errors are in the parentheses. Level of significance $^{*}p < .1$, $^{**}p < .05$, $^{***}p < .01$

Table 4. Correlates of receiving solar-irrigation-pump (probit marginal effects)

	Dependent variable: SIP user	
	(1)	*(2)*
Social networks		
In the last 3 years, at least one member of the family had..		
Membership in farmers' groups	0.12***	0.082**
	(0.038)	(0.038)
Membership in saving/micro-finance groups	0.077**	0.070*
	(0.037)	(0.037)
Held a position in a government office	0.17***	0.15***
	(0.045)	(0.049)
Social identity *(base= Madheshi)*		
Brahmin/Chhetri	-0.036	0.006
	(0.047)	(0.052)
Janajati	-0.047	0.050
	(0.124)	(0.115)
Dalit/Tharu	0.055	0.036
	(0.067)	(0.065)
Muslim	-0.17**	-0.10
	(0.080)	(0.088)
Assets and Income		
Asset index (base= Top 20%)		
Bottom 40 percent	-0.28***	-0.15**
	(0.049)	(0.059)
Middle 40 percent	-0.19***	-0.086
	(0.049)	(0.053)
Employment/cash transfer		
At least one member is wage-employed	0.0002	-0.020
	(0.040)	(0.039)
At least one member is self-employed	0.007	0.021
	(0.045)	(0.043)
Household received cash/kind transfer	0.16***	0.19***
	(0.036)	(0.037)
Control covariates	No	Yes
Observations	**653**	**653**

Notes: Point estimates are marginal effects. Standard errors in parentheses. Level of significance * $p < .1$, ** $p < .05$, *** $p < .01$. Control covariates include household characteristics, agricultural characteristics, primary source of news and information, and training on irrigation and vegetable cultivation.

Table 5. Correlates of fuel pump use for agricultural water extraction (probit marginal effects)

	Diesel pumps	Electric pumps
	(1)	*(2)*
SIP program participation *(base: never applied)*		
Received SIP	-0.044	-0.19***
	(0.0413)	(0.0414)
Applied for SIP, but did not receive	0.092**	-0.079*
	(0.0438)	(0.0429)
Social networks. *In the last 3 years at least one member of the family had…*		
Membership in farmers' groups	-0.027	0.018
	(0.0347)	(0.0357)
Membership in saving/micro-finance groups	-0.022	0.041
	(0.0318)	(0.0329)
Held a position in a government office	-0.029	-0.0028
	-0.027	0.018
Social identity *(base= Madheshi)*		
Brahmin/Chhetri	-0.17***	0.26***
	(0.0518)	(0.0551)
Janajati	-0.31***	0.24**
	(0.110)	(0.121)
Dalit/Tharu	-0.059	-0.087
	(0.0567)	(0.0539)
Muslim	0.15**	-0.19***
	(0.0619)	(0.0656)
Assets and Income		
Asset index (base= Top 20%)		
Bottom 40 percent	-0.097*	-0.042
	(0.0530)	(0.0551)
Middle 40 percent	-0.097**	-0.031
	(0.0477)	(0.0480)
Employment/cash transfer		
At least one member is wage-employed	-0.094***	-0.028
	(0.0333)	(0.0361)
At least one member is self-employed	-0.026	0.061

	(0.0369)	(0.0385)
Household received cash/kind transfer	-0.020	0.082**
	(0.0344)	(0.0349)
Control covariates	Yes	Yes
Observations	**653**	**653**

Notes: Point estimates are marginal effects. Standard errors in parentheses. Level of significance * $p < .1$, ** $p < .05$, *** $p < .01$

Control covariates include household characteristics (*household size, head's gender, head's education, and if household has a migrant member*), primary source of news and information (*radio, TV, internet, and newspaper*), number of crops cultivated, number of irrigated crops, indicators for training on vegetable cultivation, irrigation, and repair and maintenance of irrigation pumps.

Table 6. Intensity of using diesel and electric pumps for agricultural water extraction (hours/season)

	Rainy season		Dry season	
	Diesel pump	Electric pump	Diesel pump	Electric pump
	(1)	*(2)*	*(3)*	*(4)*
SIP program participation *(base= never applied)*				
Received SIP	-16.2***	-1.17	-10.70**	-0.63
	(5.936)	(9.838)	(4.888)	(3.997)
Applied for SIP, but not received	-7.27	5.74	6.83	0.84
	(5.835)	(10.11)	(4.755)	(4.524)
Social networks. *In the last 3 years at least one member of the family had…*				
Membership in farmers' groups	7.61*	13.7*	3.10	-3.03
	(4.282)	(7.864)	(3.716)	(3.661)
Membership in saving/micro-finance groups	-1.97	-6.73	1.52	1.57
	(3.635)	(7.622)	(3.658)	(3.401)
Held a position in a government office	5.27	-6.53	1.76	-5.99
	(5.043)	(12.55)	(4.904)	(5.461)
Social identity *(base= Madheshi)*				
Brahmin/Chhetri	3.11	20.0**	0.61	-6.29
	(6.255)	(9.868)	(7.006)	(4.558)
Janajati	-8.63	64.5***	-8.45	-13.0***
	(10.28)	(20.37)	(7.614)	(4.520)
Dalit/Tharu	-4.29	-3.39	-13.7***	-10.4**
	(5.984)	(9.989)	(4.764)	(4.149)
Muslim	-7.95	-19.8	-4.31	-2.71
	(7.280)	(16.57)	(5.709)	(13.63)
Assets and Income				
Asset index (base= Top 20%)				
Bottom 40 percent	17.8***	24.0*	0.62	3.75
	(5.937)	(12.60)	(5.220)	(4.881)
Middle 40 percent	8.52*	16.4	-2.25	2.68
	(4.656)	(11.110)	(4.515)	(3.832)
Employment/cash transfer				
At least one member is wage-employed	-9.87***	1.04	-0.68	0.74
	(3.694)	(7.585)	(3.707)	(3.211)

At least one member is self-employed	2.34	14.1	4.20	0.30
	(4.577)	(8.633)	(3.973)	(3.714)
Household received cash/kind transfer	-4.90	-0.82	0.14	-3.63
	(3.920)	(9.275)	(3.660)	(3.820)
Control covariates	Yes	Yes	Yes	Yes
Constant	23.1*	38.3	0.28	15.7
	(12.95)	(34.25)	(11.33)	(14.17)
Observations	**508**	**264**	**508**	**264**

Notes: Point estimates are marginal effects. Standard errors in parentheses. Level of significance * $p < .1$, ** $p < .05$, *** $p < .01$

Other control covariates include household characteristics (*household size, head's gender, head's education, and if household has a migrant member*), primary source of news and information (*radio, TV, internet, and newspaper*), number of crops cultivated, number of irrigated crops, indicators for training on vegetable cultivation, irrigation, and repair and maintenance of irrigation pumps.

FIGURES

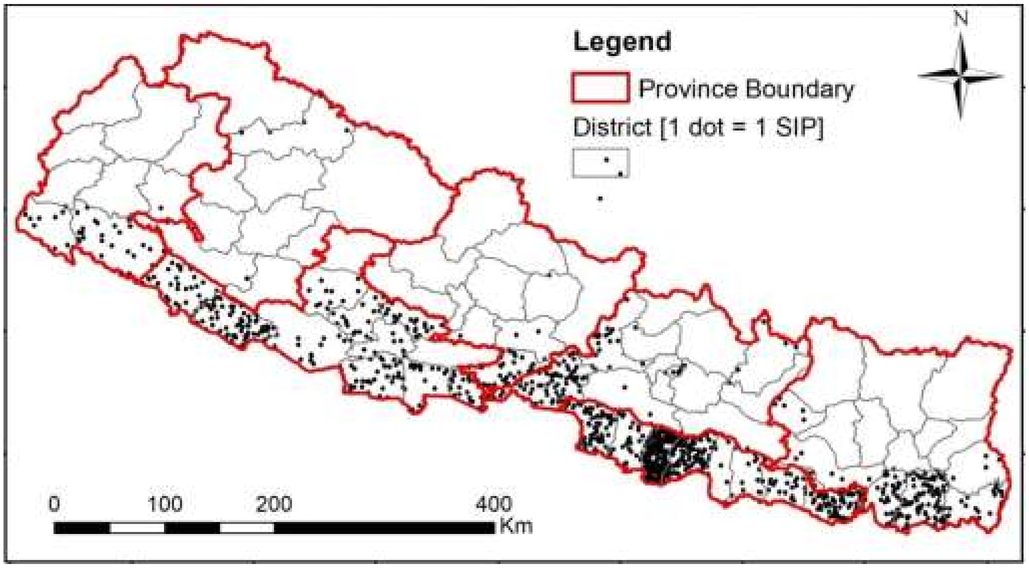

Figure 1. Administrative map of Nepal showing districts where SIPs have been distributed.

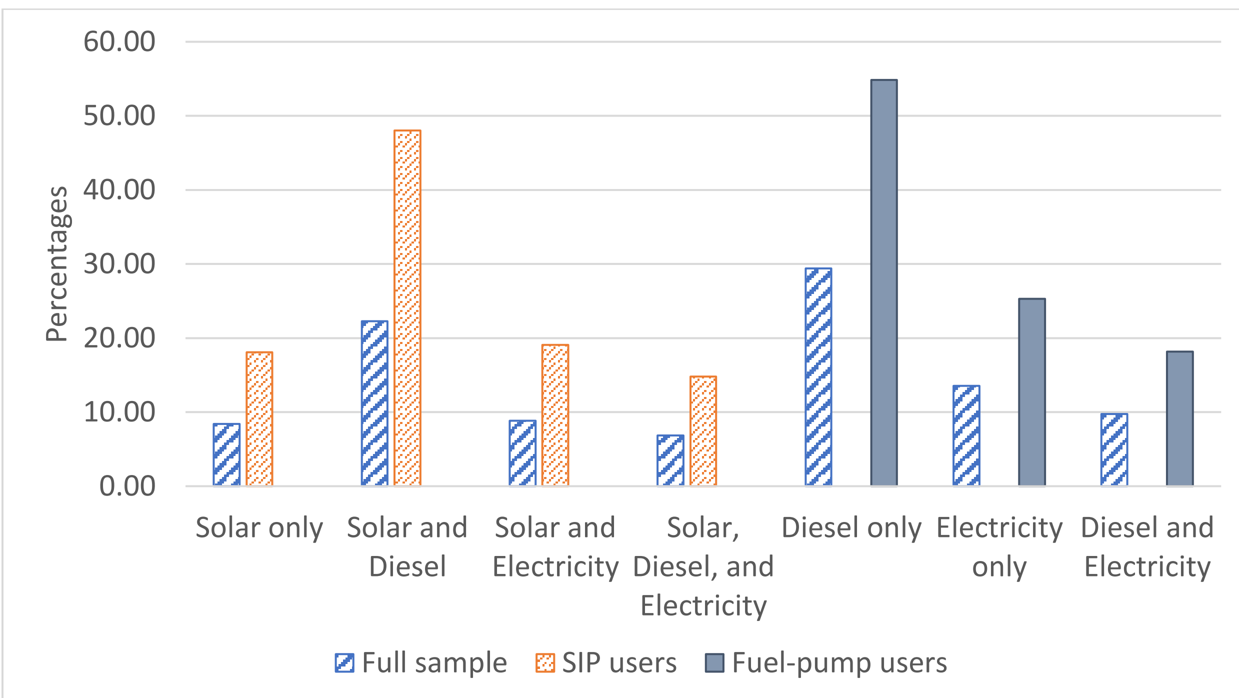

Figure 2. Energy sources used for agricultural water extraction (irrigation, fishpond, and livestock)