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Can Solar Irrigation Drive Sustainable Rural Energy Transition? Evidence from Madhesh Province, Nepal

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Abstract: Diesel-powered groundwater irrigation remains a major agricultural energy pathway in drought-prone Madhesh Province, Nepal, exposing smallholder households to recurring fuel costs, price volatility, and climate-related production risk. This study combines a structured survey of 273 farm households across all eight districts of Madhesh Province with field-based technical assessments, secondary solar resource information, inferential statistics, and a subsidy-sensitive life-cycle cost model to evaluate the adoption potential of solar irrigation pumping systems (SIPs). Diesel was reported as a primary or secondary pumping source by 92.7% of households surveyed, and the mean annual irrigation expenditure was NPR 18,423 (SD 6,712). Annual irrigation costs differed significantly across pumping-system groups (Kruskal-Wallis $H = 35.3$, $p < 0.001$) and were weakly but significantly correlated with landholding size ($r = 0.24$, $p < 0.001$). Drought exposure was strongly associated with a reported increase in irrigation demand (chi-square = 254.3, $p < 0.001$). Although 68.1% of respondents expressed unconditional or subsidy-conditional willingness to adopt solar irrigation, a multivariable logistic model identified no statistically significant individual-level predictors of positive stated willingness, including age, landholding size, household size, irrigation cost, education, prior subsidy awareness, or drought exposure (pseudo- $R^2 = 0.019$, $p = 0.53$). The financial analysis shows that a 60% capital subsidy reduces the 20-year net present cost of SWPS from approximately NPR 422,598 to NPR 200,942 and shortens the simple payback period relative to a new diesel pump from 15.4 to 4.9 years. These findings indicate that, under the tested assumptions, the transition from diesel to solar irrigation in Madhesh Province is constrained less by farmer willingness than by affordability, information, and service-support barriers. For energy-for-sustainable-development policy, broad-based subsidy communication, reliable after-sales service, and hybrid solar-grid configurations may therefore be more effective than narrow socio-demographic targeting.

Keywords: solar irrigation pumps; diesel irrigation; life-cycle cost; technology adoption; drought; subsidy policy

1. Introduction

Agriculture accounts for approximately 70% of global freshwater withdrawals, making irrigation one of the largest water-use activities worldwide. (Food and Agriculture Organization of the United Nations, 2021). At the same time, irrigated agriculture depends on reliable and affordable energy for water pumping, especially where groundwater is extracted using electric or diesel-powered pumps. In much of the developing world, diesel pumps remain common due to unreliable electricity supply and load-shedding, exposing farmers to fuel dependence, local air pollution, greenhouse gas emissions, and climate-related production risks.(Adhikari et al., 2019). As climate change intensifies droughts and increases irrigation demand, replacing fossil-fuel irrigation with renewable-energy technologies has become a critical component of sustainable agricultural development.

Agriculture underpins rural livelihoods and food security across Nepal's Terai plains, where productivity is closely tied to reliable and affordable irrigation. In this context, irrigation energy is not only a farm input but also an instrument of rural development, climate adaptation, and household economic resilience. Although Nepal's electricity supply has expanded in recent years, farm-level access, voltage quality, and seasonal reliability remain uneven in many rural areas. Diesel pumps continue to fill this reliability gap, particularly for groundwater-based irrigation. However, they also expose farmers to fuel price volatility, recurring operating costs, and local air pollution and greenhouse gas concerns. (Adhikari et al., 2019; Foster et al., 2021; Jayarathne et al., 2018).

Madhesh Province, which includes Saptari, Siraha, Dhanusha, Mahottari, Sarlahi, Rautahat, Bara, and Parsa districts, is one of Nepal's most agriculturally important regions. It is also increasingly exposed to climate-related water stress. Erratic monsoon timing, prolonged dry spells, and pressure on groundwater recharge have intensified irrigation demand, and the Government of Nepal declared Madhesh a disaster crisis zone following the severe 2025 monsoon-season drought. (Shrestha et al., 2025). Under these conditions, groundwater pumping has become central to maintaining crop production, while dependence on diesel can deepen household financial stress precisely when irrigation demand is highest.

Solar irrigation pumps (SIPs) have emerged internationally and within Nepal as a technically mature alternative to diesel pumping. However, their economic viability depends heavily on system utilization, subsidy design, access to financing, maintenance services, and groundwater governance (Closas & Rap, 2017; Hilarydoss, 2021; Paudel & Adhikari, 2025; terang & Baruah, 2023). Solar-resource assessments indicate that Nepal has favorable photovoltaic potential, including in the Terai belt, supporting the technical case for solar water pumping where water availability and pumping depth are suitable (ESMAP, 2017). Nepal's Alternative Energy Promotion Center (AEPCC) has promoted solar irrigation through

capital subsidy mechanisms, including up to 60% investment support under relevant renewable energy subsidy arrangements (Alternative Energy Promotion Centre, n.d.). However, previous research in Nepal and South Asia shows that high upfront cost, weak awareness of subsidy and financing mechanisms, limited after-sales service, institutional gatekeeping, and unequal access for women and marginalized farmers continue to constrain scale-up (Bhattarai et al., 2025; Kafle et al., 2022; Varshney et al., 2026).

Unlike previous studies that primarily evaluate the technical or economic performance of solar irrigation systems, this study integrates household adoption behavior, drought-induced irrigation stress, subsidy-sensitive life-cycle economics, and direct diesel-displacement emissions within a single analytical framework. This integrated perspective enables identification of whether adoption barriers arise primarily from farmer preferences or from structural constraints on affordability, information, and service support, providing evidence directly relevant to energy-for-sustainable-development policy in climate-vulnerable agricultural regions. The analytical logic is summarized in Figure 1, which links climate variability, irrigation demand, diesel dependence, household cost pressures, and conditions for solar-irrigation adoption. The specific objectives are to: (i) characterize the scale and cost of diesel-dependent irrigation and its household-level correlates; (ii) test associations between drought exposure, irrigation-system type, irrigation cost, and adoption-related outcomes; (iii) estimate household-level correlates of stated willingness to adopt solar irrigation; (iv) compare diesel and solar irrigation costs under alternative subsidy and discount-rate scenarios; and (v) estimate the direct CO₂ implications of replacing diesel pumping with solar irrigation.

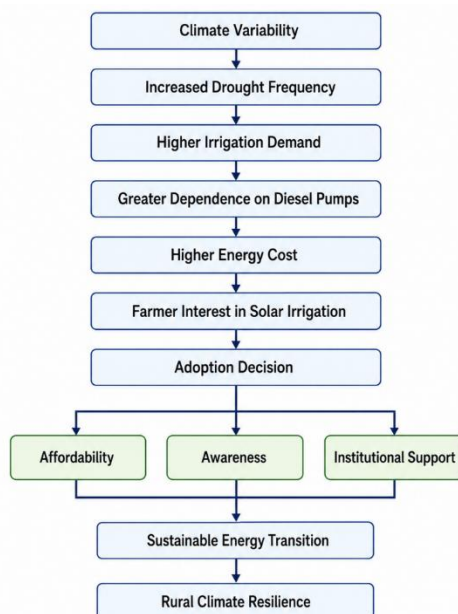


Figure 1. Conceptual framework linking climate variability, drought-induced irrigation demand, diesel dependence, household cost pressure, solar-irrigation adoption conditions, and rural climate resilience

2. Materials and Methods

2.1. Study area and design

The study was conducted across 20 municipalities and rural municipalities in all eight districts of Madhesh Province. Local governments were selected to provide east-west provincial coverage and to include areas where pump-based groundwater irrigation is commonly used. Within selected local governments, enumerators worked through local agricultural contacts and field visits to identify farm households using pumping or tubewell/boring irrigation. Participation was voluntary and only consenting respondents were interviewed. The wider baseline study used a mixed-method design, including a structured farm-household survey, key informant interviews, focus group discussions, and technical field assessment of irrigation sites. This study focuses on quantitative household surveys and the associated technical and economic data, while using qualitative observations only for contextual interpretation. Qualitative information was not subjected to formal coding or thematic analysis in this paper. Instead, observations from field discussions, key informant interactions, and technical site visits were used only to contextualize the quantitative findings and identify practical implementation concerns.

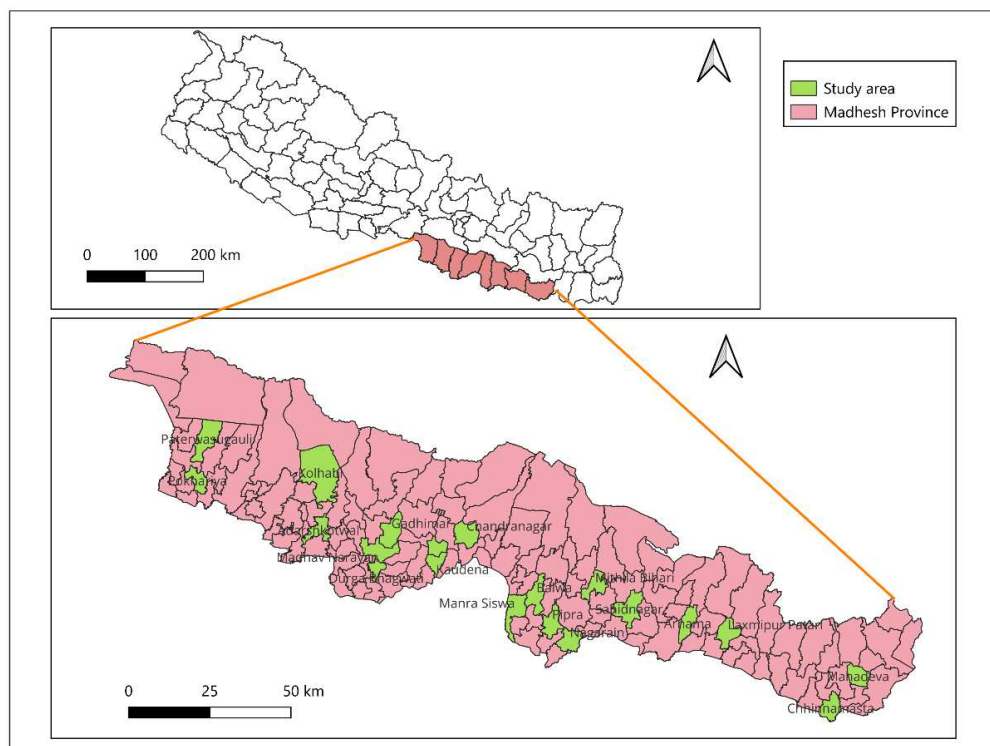


Figure 2. Study area map of Madhesh Province and surveyed municipalities/rural municipalities

2.2. Sampling and data collection

The target population comprised farm households in Madhesh Province using pumping or tubewell/boring irrigation, estimated at 483,463 holdings according to the National Sample Census of Agriculture 2021/22 (National Statistics Office, 2023). With an unknown true adoption proportion ($p = 0.5$), the minimum required sample at 90% confidence and a 5% margin of error was approximately 273 households using the standard proportion-based

sample-size formula, $n = Z^2 p(1-p)/e^2$ (James E. Bartlett et al., 2001). The realized sample was proportionally allocated across the eight districts according to each district's share of pumping and tubewell/boring irrigation holdings. During survey planning, a target of at least 30% female respondents was set; however, the realized female response rate was only 4.8%, which limits the validity of gender-disaggregated inference and is addressed in the limitations section. Because households were identified through local contacts and field accessibility, the sample should be interpreted as a structured baseline sample rather than a fully random provincial sample. Sampling and nonresponse bias may therefore remain, particularly if less accessible households, women decision-makers, or marginalized groups were less likely to be reached or willing to participate (Groves, 2006; Groves & Peytcheva, 2008). In total, 273 household questionnaires were retained for analysis. The survey covered landholding size, cropping pattern, irrigation source and system type, pump characteristics, fuel and electricity costs, experience with maintenance, drought exposure, awareness of solar irrigation and AEPC subsidy provisions, stated willingness to adopt solar irrigation, and gender dimensions of irrigation decision-making.

2.3. Statistical analysis

Continuous variables (age, household size, landholding, annual irrigation cost, and annual fuel cost) were summarized using means, standard deviations, and medians. The reported main irrigation system was harmonized into four mutually exclusive groups: diesel-only, diesel-plus-electric (dual system), electric-only, and other/solar-mixed. Education collapsed into three ordered categories: no formal/informal education, primary/lower-secondary, and secondary or above. Associations between categorical variables, including education group and subsidy awareness; drought experience and reported increase in irrigation need; irrigation-system group and district; and subsidy awareness and stated willingness to adopt solar irrigation, were tested using Pearson's chi-square test of independence, with Cramer's V reported as the effect size. Fisher's exact test was used for the gender-by-adoption-willingness comparison because of small cell counts. Differences in annual irrigation costs across irrigation-system groups were tested using the Kruskal-Wallis one-way analysis of ranks because the costs were right-skewed. Pearson correlation coefficients were computed between landholding size, household size, annual irrigation cost, and annual fuel cost. Finally, a multivariable binary logistic regression was estimated to identify correlates of positive stated willingness to adopt solar irrigation, defined as unconditional or subsidy-conditional willingness (coded 1) versus unsure or unwilling responses (coded 0). Covariates were age, total landholding, household size, annual irrigation cost, prior awareness of the AEPC subsidy, ordinal education score, and drought exposure. All statistical tests were conducted in Python using SciPy and statsmodels with a two-sided significance threshold of $\alpha = 0.05$. Results are interpreted as associations rather than causal effects. Because household identification was not fully random at all stages, p-values are interpreted as exploratory evidence of association within the structured survey sample.

rather than as definitive population-level inference for all farm households in Madhesh Province.

The four-category willingness response was dichotomized to distinguish respondents expressing a positive adoption disposition from those who were uncertain or unwilling. This binary specification was selected because the study's primary policy interest was whether households were broadly open to adoption under either current or subsidy-supported conditions. However, the loss of information from combining unconditional and subsidy-conditional willingness is acknowledged as a limitation.

2.4. Life-cycle cost and sensitivity analysis

A 20-year life-cycle cost (LCC) comparison was constructed from the farmer's financial perspective between a new 3-5 HP diesel pump and an equivalent-capacity 4.5-7.5 kWp solar irrigation pumping system (SIPs). The diesel case included an initial capital cost of NPR 45,000, annual recurring fuel and maintenance costs that escalated at 12% per year to reflect fuel price escalation, and pump replacement at year 10. The SIPs case included a full system capital cost of NPR 375,000, an annual operation and maintenance cost of NPR 2,000, a component replacement cost equal to 25% of the full capital cost at year 10, and a residual value equal to 10% of the farmer's capital contribution at year 20. The analysis extended a single-scenario comparison into a two-way deterministic sensitivity analysis, recomputing the 20-year net present cost and simple payback period of SWPS relative to a new diesel pump across five subsidy levels (0-80% of capital cost, in 20-percentage-point increments) and five discount rates (6-14%, in 2-percentage-point increments), with all other parameters held constant. This deterministic analysis identifies the relative influence of key policy parameters. However, it does not substitute for a full probabilistic uncertainty analysis of capital costs, diesel fuel escalation, O&M costs, component lifetimes, utilization rates, and site-specific pumping conditions.

The net present cost was calculated as the discounted sum of all capital, operating, maintenance, replacement, and residual-value cash flows over the 20-year analysis period. The general form used was:

$$NPC = C_0 + \sum \frac{C_t}{(1+r)^t} - \frac{RV}{(1+r)^{20}}$$

Where NPC is the net present cost; C_0 is the initial farmer-facing capital cost; C_t is the annual or replacement cost incurred in year t ; r is the discount rate; and RV is the residual value at the end of the project period. For subsidized SIP cases, the farmer-facing capital cost was calculated after deducting the applicable capital subsidy.

2.5. Environmental implications of diesel replacement

A first-order environmental implication calculation was added to estimate direct on-farm CO₂ emissions avoided when SIPs replace diesel pumping. The calculation used the survey-reported fuel-use variable, i.e., annual fuel consumed.

Direct annual CO₂ emissions from diesel irrigation were calculated using:

$$E_{co_2} = D_{mean} \cdot EF_{diesel}$$

Where, D_{mean} is the mean annual diesel consumption per household and EF_{diesel} is the direct-combustion emission factor for diesel.

An emission factor of 2.68 kg CO₂ per litre of diesel was applied, consistent with standard direct-combustion accounting approaches (Intergovernmental Panel on Climate Change, 2006). Household-level emissions were scaled to the full 273-household survey sample and to a 20-year project period by multiplying the annual household estimate by the number of surveyed households and the project lifetime, assuming constant annual diesel use.

Solar irrigation pumping was treated as having zero direct on-site CO₂ emissions during operation. The estimate, therefore, represents only the avoided direct diesel combustion emissions. It excludes upstream fuel-cycle emissions and embodied emissions from PV module manufacturing, transport, installation, component replacement, and end-of-life treatment; therefore, the results should be interpreted as a direct diesel-displacement estimate rather than a complete life-cycle carbon footprint.

To connect the emissions results to their relevance to sustainable development, the avoided-diesel interpretation was also qualitatively linked to the Sustainable Development Goals. The SDG linkage was assessed as a policy and development co-benefit interpretation, not as a separate quantitative SDG scoring exercise. The most relevant goals were SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), SDG 2 (Zero Hunger), and SDG 3 (Good Health and Well-being), in line with the United Nations 2030 Agenda.

3. Results

3.1. Household and Irrigation Profile

The 273 surveyed households were predominantly represented by male respondents (95.2%) and female respondents (4.8%). The mean respondent age was 50.1 years (SD 10.2), and the mean household size was 7.0 people (SD 2.7). The mean total landholding was 1.70 bigha (SD 1.2), of which 1.45 bigha was irrigated. Table 1 summarizes the continuous household and irrigation variables used in the analysis.

Table 1. Descriptive statistics for continuous household and irrigation variables

Variable	Mean	Standard Deviation	Median	Min.	Max.
Respondent age (years)	50.1	10.2	51.0	16	82
Household size (persons)	7.0	2.7	6.0	3	23
Total landholding (bigha)	1.7	1.2	1.5	0.2	12.0
Irrigated landholding (bigha)*	1.5	1.1	1.2	0.3	11.0

Annual fuel consumption(litres)	81.1	29.87	85	9	280
Annual irrigation cost (NPR)	18,423	6,712	20,070	2,000	62,440

*In Nepal, 1 bigha of land is equivalent to 0.6772631616 hectares of land

The annual fuel-cost variable represents farmer-reported annual expenditure associated with diesel-based irrigation, which may include fuel purchase as well as bundled pumping-service payments, operator charges, pump rental, or transport costs where farmers did not purchase diesel separately. Therefore, it should not be interpreted as a direct multiplication of reported diesel litres by a uniform retail diesel price.

Diesel was reported as part of the household's main pumping arrangement by 92.7% of respondents: 79.5% relied on diesel only, 13.2% operated a dual diesel-and-electric system, 5.1% relied on electric pumping only, and 2.2% reported another arrangement, including a small number of existing solar or mixed solar users. This distribution, shown in Figure 3, indicates that diesel dependence was dominant among the surveyed households, with diesel as the main irrigation source for roughly 4 of the 5 households.

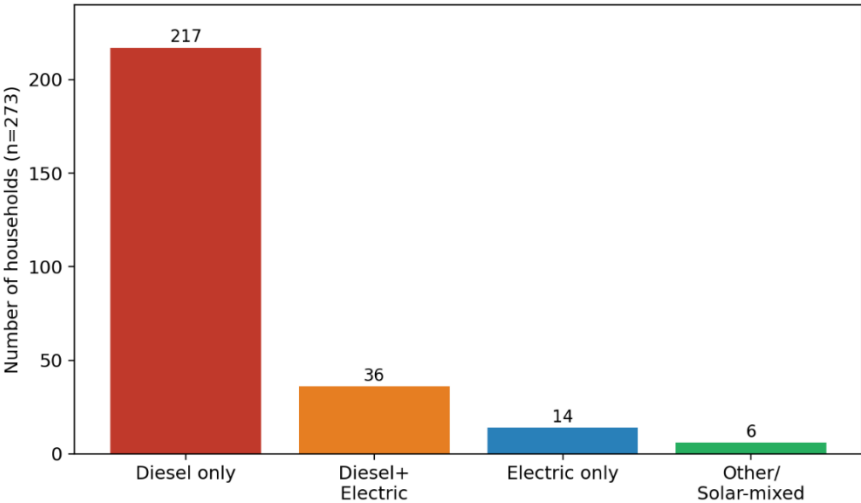


Figure 3. Main irrigation pumping system reported by surveyed households

3.2. Correlates of irrigation cost burden

Annual irrigation cost differed significantly across the four pumping-system groups (Kruskal-Wallis $H = 35.3$, $df = 3$, $p < 0.001$). As shown in Figure 4, households operating a dual diesel-and-electric system reported the highest median annual cost (NPR 23,685), followed by diesel-only households (NPR 18,955); electric-only households reported the lowest median cost (NPR 12,265). This pattern is consistent with dual-system households using diesel as a supplementary source during peak or drought periods while also maintaining an electricity connection, thereby incurring costs from both energy sources. Electric-only households reported lower costs where the grid supply was adequate.

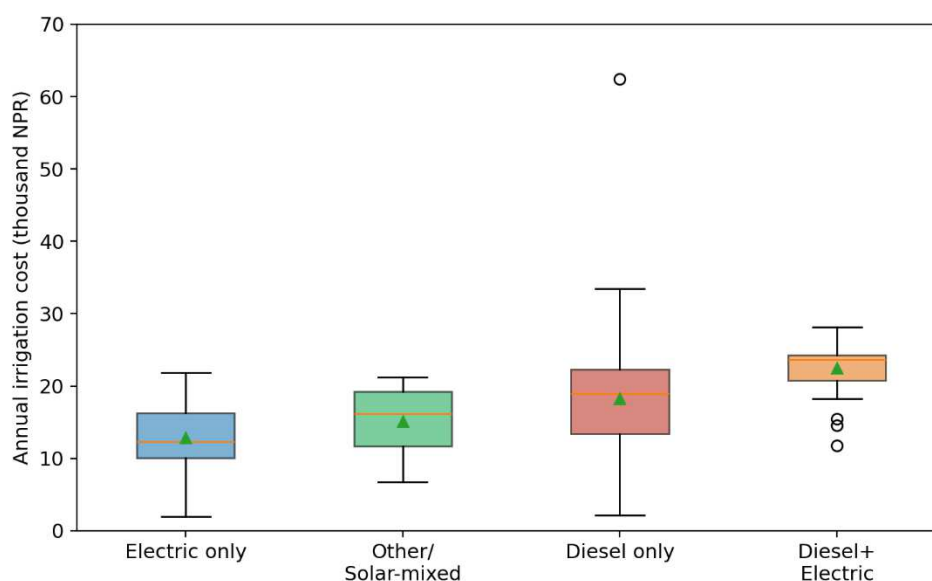


Figure 4. Annual irrigation cost (NPR) by main pumping-system group. Boxes show the interquartile range, the horizontal line shows the median, and the triangle shows the group's mean.

Landholding size was weakly but significantly and positively correlated with annual irrigation cost (Pearson $r = 0.24$, $p < 0.001$, $n = 273$) and annual fuel cost ($r = 0.23$, $p < 0.001$). Farmers cultivating larger areas, therefore, incurred modestly higher absolute irrigation expenditure, consistent with greater pumping-volume requirements. However, the size effect was small, indicating that landholding size alone explained only a limited share of the variation in cost (Figure 5). Household size was not significantly correlated with annual irrigation cost ($r = 0.07$, $p = 0.24$).

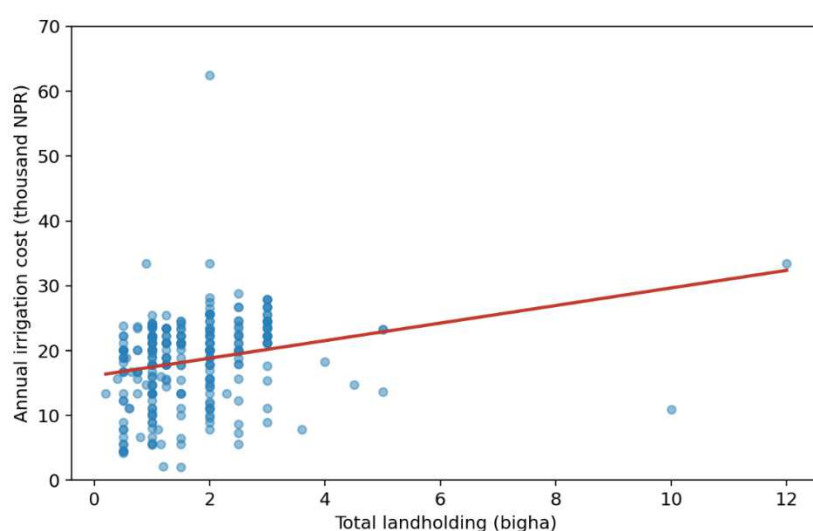


Figure 5. Relationship between total landholding (bigha) and annual irrigation cost (NPR), with linear fit.

3.3. Drought exposure and irrigation stress

A large majority of respondents (80.2%) reported experiencing drought conditions that affected irrigation. Drought experience was strongly associated with a reported increase in

irrigation needs ($\chi^2 = 254.3$, $df = 1$, $p < 0.001$, Cramer's $V = 0.97$). All 219 households reporting drought exposure also reported increased irrigation requirements, whereas only 2 of 52 households without drought exposure reported increased irrigation requirements. This near-perfect association indicates that farmers who reported drought exposure almost always also reported increased irrigation requirements. Because both variables are self-reported, cross-sectional, and conceptually closely related, the result should be interpreted as descriptive evidence of perceived irrigation stress rather than as an independent causal estimate.

3.4. Awareness and willingness to adopt solar irrigation

Only 25.6% of respondents reported prior awareness of the AEPC renewable-energy subsidy. Subsidy awareness was not significantly associated with education group (chi-square = 1.40, $df = 2$, $p = 0.50$, Cramer's $V = 0.07$), indicating that the awareness gap was broadly distributed across education levels rather than concentrated only among the least educated. Subsidy awareness was also not significantly associated with the four-category willingness-to-adopt outcome (chi-square test, $p > 0.05$), suggesting that awareness alone did not explain variation in stated adoption intent.

When asked about willingness to adopt solar irrigation, 50.9% of respondents expressed unconditional willingness, 17.2% expressed willingness conditional on subsidy support, 30.0% were unsure, and only 1.8% were unwilling (Figure 6). When the unconditional and subsidy-conditional categories are combined, 68.1% of households expressed a positive disposition toward solar adoption.

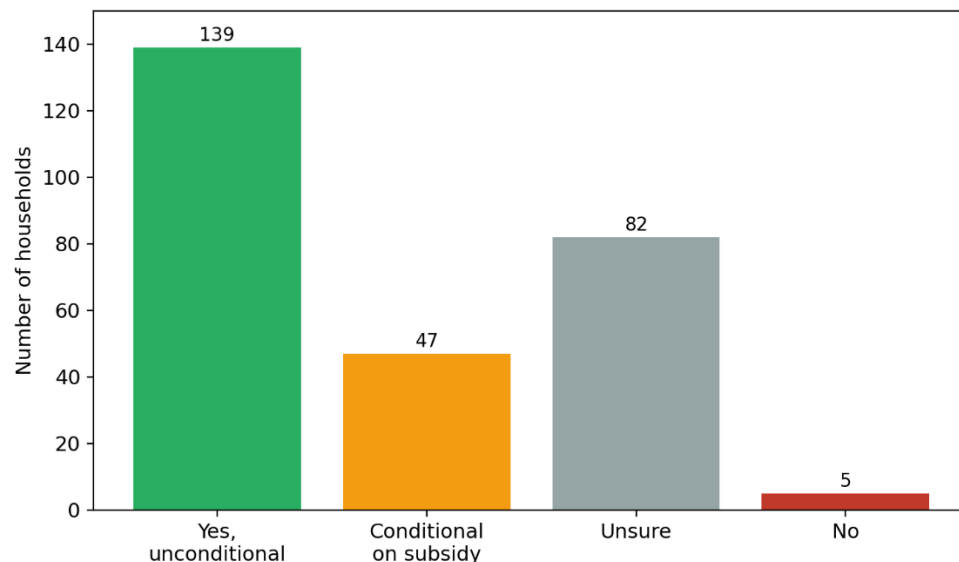


Figure 6. Reported willingness to adopt solar irrigation pumps

A multivariable logistic regression model of strong willingness, defined as unconditional or subsidy-conditional willingness, against age, total landholding, household size, annual irrigation cost, subsidy awareness, ordinal education score, and drought exposure found no individual predictors to be significant (all $p > 0.10$; Table 2). The overall model also did not significantly improve on the null model ($\chi^2 = 5.98$, $df = 7$, $p = 0.53$; pseudo- $R^2 = 0.019$). This

result should not be interpreted as proof that willingness is identical across household types. Rather, it indicates that the variables included in this model did not identify a clearly differentiated high-willingness segment within the sample. A supplementary Fisher's exact test revealed a non-significant but directionally positive association between female respondent status and strong willingness (odds ratio = 2.6, $p = 0.12$), which should be interpreted with caution given the small sample size of 13 women.

Table 2. Multivariable logistic regression predicting positive willingness to adopt solar irrigation

Predictor	Odds ratio	95% CI	p-value
Age (years)	1.02	0.99 - 1.05	0.163
Total landholding (bigha)	1.07	0.83 - 1.38	0.604
Household size (persons)	1.01	0.91 - 1.13	0.828
Annual irrigation cost, per NPR 10,000	1.191	0.750–1.891	0.460
Aware of AEPC subsidy (yes vs. no)	1.33	0.70 - 2.53	0.383
Education (ordinal score)	1.03	0.90 - 1.19	0.648
Experienced drought (yes vs. no)	0.68	0.34 - 1.39	0.294

Note: The dependent variable is positively stated willingness to adopt solar irrigation, coded 1 for unconditional or subsidy-conditional willingness and 0 for unsure or unwilling responses. CI = confidence interval. Model statistics: $N = 273$; likelihood-ratio $\chi^2 = 5.98$; $df = 7$; $p = 0.53$; pseudo- $R^2 = 0.019$.

Consistent with contextual observations from field discussions, key informant interactions, and technical site visits, the main practical barriers to adoption were limited awareness of solar irrigation technology and financing options, high upfront capital cost, concerns about theft or damage to field-based equipment, and uncertainty about system performance and maintenance. These observations were used for interpretation rather than formal qualitative inference, and they are consistent with constraints reported in the wider South Asian solar-irrigation literature.

3.5. Techno-economic comparison and sensitivity analysis

Under the baseline financial assumptions (10% discount rate and 20-year horizon), the 20-year net present cost of continued reliance on a new diesel pump was approximately NPR 514,405, compared with NPR 422,598 for an unsubsidized SIP and NPR 200,942 for a SIP receiving a 60% capital subsidy. The corresponding simple payback periods for a new diesel pump were 15.4 years without a subsidy and 4.9 years with a 60% subsidy. Figure 7 and Table 3 present the two-way sensitivity of SIPs' net present cost to subsidy rate and discount rate. Two patterns are notable. First, the present net cost is highly sensitive to the subsidy rate: moving from 0% to 80% subsidy reduces the 20-year net present cost by roughly two-thirds at any given discount rate (for example, from NPR 422,598 to NPR 127,057 at a 10%

discount rate). Second, the present net cost is comparatively less sensitive to the discount rate, varying by less than 7% across the 6-14% range tested at any fixed subsidy level, because the dominant cost component is the farmer's upfront capital contribution. Within the tested assumptions, subsidy design is therefore a more influential lever for improving SIPs' affordability than the appraisal discount rate.

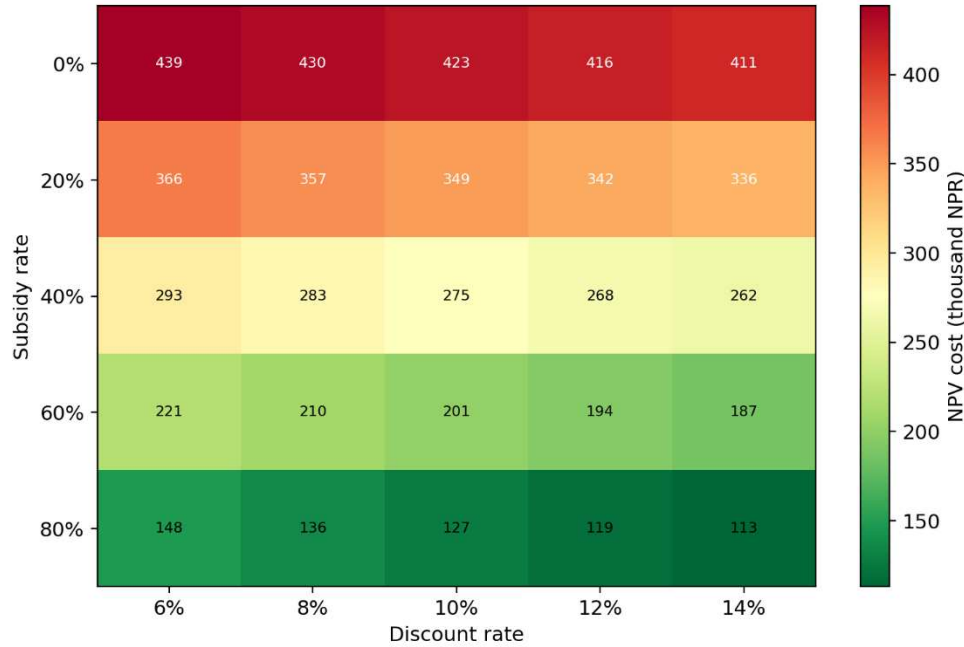


Figure 7. Sensitivity of the 20-year net present cost (NPR) of a solar water-pumping system to the subsidy rate and the discount rate.

Table 3. Sensitivity of the 20-year net present cost of SIPs (NPR) to the subsidy rate and discount rate

Subsidy rate	6%	8%	10%	12%	14%
0%	438,597	430,015	422,598	416,236	410,806
20%	365,935	356,624	348,713	342,014	336,352
40%	293,274	283,233	274,827	267,791	261,898
60%	220,612	209,842	200,942	193,569	187,443
80%	147,951	136,452	127,057	119,346	112,989

The payback period relative to a new diesel pump follows the same subsidy-driven pattern and, because of the simple-payback method used here, is independent of the discount rate: 15.35 years with no subsidy, 11.86 years at 20% subsidy, 8.37 years at 40% subsidy, 4.88 years at 60% subsidy, and 1.40 years at 80% subsidy. Taken together with the household-level willingness results, these outcomes suggest that a major barrier to solar irrigation uptake in Madhesh Province is structural and financial rather than purely attitudinal. A large share of surveyed farmers expressed openness to adoption, while the subsidy rate was the parameter with the greatest leverage over adoption economics in the deterministic LCC model.

345 3.6. Environmental implications of diesel replacement

346 Using the mean reported annual diesel consumption from the cleaned survey dataset,
347 households surveyed used 81.1 liters of diesel per household per year for irrigation pumping.
348 Applying a direct-combustion emission factor of 2.68 kg CO₂ per litre gives an estimated
349 217.3 kg CO₂ per household per year, equivalent to 4.35 tCO₂ over a 20-year project life if
350 annual fuel use remains constant. For the 273-household sample, this corresponds to
351 approximately 59.3 tCO₂ per year and 1,186 tCO₂ over 20 years. Solar pumping is treated as
352 having zero direct on-site CO₂ during operation; therefore, the figures in Table 4 represent
353 avoided direct diesel combustion emissions, not a complete PV life-cycle emissions balance.

354 From a sustainable development perspective, diesel replacement through SIPs
355 contributes most directly to SDG 7 (Affordable and Clean Energy) by shifting irrigation
356 energy from diesel to renewable electricity, and to SDG 13 (Climate Action) by reducing
357 direct fossil-fuel CO₂ emissions. It also supports SDG 2 (Zero Hunger) by improving the
358 clean-energy basis of irrigation for drought-stressed agriculture and has secondary relevance
359 to SDG 3 (Good Health and Well-being) because lower diesel use can reduce local
360 combustion-related air pollutants near farms. These SDG links strengthen the interpretation
361 of solar irrigation as both a climate-mitigation and rural-resilience intervention, rather than
362 only a household cost-saving technology.

363 Table 4. Estimated CO₂ emissions avoided through diesel replacement using the mean
364 reported annual diesel use from the survey dataset.

Scenario	Per the surveyed household (mean)	Surveyed sample
Estimated annual diesel use (liters)	81.1	22,140
Estimated annual CO ₂ avoided if fully displaced by solar (tCO ₂)	0.22	59.3

365 4. Discussion

366 This study provides an integrated assessment of the irrigation-energy transition in
367 drought-affected Madhesh Province by linking evidence on household adoption, drought-
368 related irrigation stress, subsidy-sensitive life-cycle economics, and direct diesel-
369 displacement emissions. The findings support the conceptual framework in Figure 1: climate
370 variability increases irrigation demand; higher irrigation demand reinforces diesel
371 dependence; diesel dependence raises household cost exposure; and interest in solar irrigation
372 becomes meaningful only when affordability, information, finance, and service support are
373 addressed together.

374 The high reported diesel dependence in Madhesh Province is consistent with evidence
375 from Nepal's Terai and the wider Indo-Gangetic Plain, where diesel pumping continues to
376 bridge gaps in reliable irrigation energy despite its cost and emissions burden (Adhikari et
377 al., 2019; Foster et al., 2021). Similar cost-driven motivations for solar pumping have been

reported in Assam, India, where a comparative techno-economic and environmental assessment found that PV pumping can reduce operating costs and CO₂ emissions relative to diesel pumping when solar resources and utilization are adequate (Terang & Baruah, 2023). The Nepal results, therefore, fit a broader South Asian pattern: solar irrigation is technically attractive, but adoption depends on the interplay among capital costs, financing, pumping depth, service reliability, and water availability.

The Bangladesh literature also supports the importance of combining adoption analysis with economic outcomes. (Sunny et al., 2022) Using survey data from rice farmers in northern Bangladesh, the study found that adoption of solar irrigation was shaped by farmers' knowledge and other contextual factors and was associated with lower irrigation costs and higher returns. In the present Madhesh sample, however, the logistic regression did not identify statistically significant socio-economic predictors of strong willingness. This difference may arise because the current model measured stated willingness rather than observed adoption and did not include income, credit access, groundwater depth, ownership of irrigation assets, or risk perception. The result should therefore be read as evidence that simple demographic targeting is insufficient, not as evidence that adoption is random.

Evidence from Pakistan highlights another policy lesson. Solar irrigation can reduce energy costs and fossil fuel use, but weak groundwater governance can create rebound risks by making pumping cheaper and more widely available. (Closas & Rap, 2017; Hussain et al., 2023). This is directly relevant to Madhesh Province, where the households surveyed reported significant drought-related increases in irrigation needs. Solar promotion should therefore be coupled with groundwater-aware design, appropriate pump sizing, efficient water application, and local monitoring, rather than treated solely as an energy-substitution program.

The findings also connect with evidence from Sub-Saharan Africa. Recent work from Ethiopia shows that solar pumps and water-harvesting irrigation technologies can improve smallholder income and food security indicators. However, their benefits depend on complementary agricultural inputs, financing schemes, market access, and technical support. (Negera et al., 2025). This is consistent with the Madhesh findings, which showed that farmers stated that willingness alone is not enough. Productive-use energy technologies create development value when embedded within a broader support system that includes agronomic services, maintenance networks, credit, and inclusive outreach.

The emissions estimate adds a climate-mitigation dimension to the adoption and affordability results. Although the direct avoided emissions per household appear modest when calculated from reported annual fuel expenditure, aggregate benefits become meaningful when scaled across diesel-dependent irrigation users. More importantly, the emissions result complements the financial analysis: a 60% subsidy improves farmer-facing economics, while diesel displacement simultaneously reduces direct fossil-fuel emissions and fuel-price exposure. This combination of affordability, resilience, and mitigation is central to the study's contribution to energy-for-sustainable-development.

418 4.1. Policy implications

419 The results imply that solar-irrigation scale-up should be designed as a multi-level policy
420 package rather than a standalone capital subsidy. At the national level, subsidy design should
421 be combined with concessional credit, transparent eligibility criteria, simplified application
422 procedures, and integration with renewable energy, agricultural mechanization, and climate
423 adaptation programs. National agencies should also develop minimum technical standards,
424 after-sales-service requirements, and groundwater safeguards for subsidized systems.

425 At the provincial level, Madhesh Province can prioritize broad-based awareness
426 campaigns through agricultural extension offices, cooperatives, farmer groups, local
427 suppliers, and irrigation user institutions. Because subsidy awareness was low and not
428 concentrated in a single educational group, communication should not rely solely on written
429 notices or highly formal channels. Provincial programs should also support technician
430 training, the availability of spare parts, and demonstration sites in drought-prone
431 municipalities.

432 At the local level, municipalities and rural municipalities can strengthen implementation
433 by identifying diesel-dependent irrigation clusters, facilitating group or cooperative
434 financing, supporting shared maintenance centers, coordinating theft-prevention measures,
435 and linking solar pumping with efficient irrigation practices. Local targeting should pay
436 special attention to women farmers, tenant farmers, smallholders, and marginalized
437 households, as the current sample was not sufficiently gender-representative to determine
438 whether these groups face distinct adoption constraints.

439 5. Limitations

440 Several limitations should be considered when interpreting these results. First, the cross-
441 sectional design measures stated willingness rather than observed adoption behavior; the
442 logistic regression should therefore be interpreted as a model of self-reported disposition
443 rather than realized technology uptake. Future work should validate the stated willingness
444 against actual purchase, subsidy application, installation, and sustained use behavior through
445 longitudinal or experimental designs. The regression model also did not include several
446 variables that may influence solar-irrigation adoption, including household income, caste or
447 ethnicity, tenancy status, access to credit, groundwater depth, pump ownership, prior
448 exposure to solar technologies, and risk perception. The absence of statistically significant
449 predictors should therefore be interpreted as a limitation of the measured model rather than
450 evidence that household and institutional differences are irrelevant. Second, the realized
451 female sample ($n = 13$) is too small for robust gender-stratified inferential analysis, and the
452 gender-related findings are exploratory. Future survey rounds should purposively oversample
453 female-headed households and women irrigation decision-makers. Third, the willingness-to-
454 pay variable collected in the survey instrument showed almost no variation across
455 respondents, with over 99% of values within 2% of NPR 25,000, and was therefore excluded
456 from the regression analysis. A revised survey instrument using an open-ended, payment-

card, or bidding-format willingness-to-pay elicitation would strengthen future demand-side affordability analysis. Fourth, the LCC model uses deterministic point estimates for capital cost, fuel escalation, component lifetime, and O&M rather than site-specific quotations and probabilistic uncertainty ranges. Future research should integrate Monte Carlo simulation, stochastic fuel-price trajectories, groundwater-depth variability, solar-resource uncertainty, farmer income uncertainty, and utilization-rate variation to produce probabilistic estimates of long-term investment performance. Fifth, the emissions analysis estimates only directly avoided diesel-combustion CO₂ and does not include upstream fuel-cycle emissions or embodied emissions from PV manufacturing, installation, replacement, and end-of-life management. A full life-cycle environmental assessment would be required to more comprehensively estimate net climate benefits. Sixth, the sample was structured and geographically broad but not fully random at every stage; nonresponse and accessibility biases may limit generalizability to all farm households in Madhesh Province. Finally, all associations are correlational due to the observational, cross-sectional design. Causal interpretation would require longitudinal, experimental, or quasi-experimental research designs. Because the willingness outcome was dichotomized, differences between unconditional willingness and subsidy-conditional willingness were not modeled separately. Future studies could apply multinomial or ordinal models to preserve the full structure of adoption-intention responses.

6. Conclusion

This study shows that solar irrigation in drought-affected Madhesh Province is not only a technical substitute for diesel pumps but also an energy-for-development intervention that links household affordability, climate resilience, and cleaner agricultural energy use. The household evidence indicates near-universal dependence on diesel among surveyed pump users, strong perceived increases in irrigation demand during droughts, and broad interest in solar irrigation. However, the absence of significant socio-economic predictors of positive stated willingness suggests that adoption barriers are not confined to one easily identifiable demographic group. The main constraints are structural: high upfront costs, limited awareness of subsidies, limited access to financing, service uncertainty, and field-level risks such as theft and maintenance issues.

The economic and environmental analyses reinforce this interpretation. A 60% capital subsidy substantially improves farmer-facing affordability, reducing the SIP's present net cost and bringing the simple payback period below five years under the tested assumptions. Diesel replacement also offers direct emissions benefits, with the central estimate indicating avoided direct CO₂ emissions of about 0.22 tCO₂ per household per year. As climate variability increases irrigation demand across South Asia, accelerating the transition from diesel to solar irrigation will require policy interventions that simultaneously improve affordability, strengthen institutional support, expand farmer awareness, ensure reliable maintenance, and guard against unsustainable groundwater extraction. Integrating these

dimensions can promote cleaner agricultural energy systems, improve rural resilience, and contribute to sustainable development goals.

Declarations

Ethics approval and consent to participate: Respondents were informed of the study's purpose before the interview; participation was voluntary, and informed consent was obtained. No personally identifiable information is reported.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data availability

The anonymized dataset and analysis code may be made available by the corresponding author upon reasonable request, subject to institutional and ethical restrictions.

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