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SOLARIZED AGRICULTURAL TUBE WELLS AS A CATALYST FOR AGRICULTURAL PRODUCTIVITY AND SUSTAINABLE DEVELOPMENT IN DISTRICT KARAK, KHYBER PAKHTUNKHWA, PAKISTAN.

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ABSTRACT

Reliable irrigation and affordable pumping energy are vital constraints to agricultural production in the semi-arid areas of Pakistan. This study evaluated perceived efficacy of solarized agricultural tube wells in two villages, Atti Khel and Painda-Khel of Takht-e-Nasrati Tehsil, District Karak, Khyber Pakhtunkhwa. A cross-sectional household survey was conducted among 57 respondents selected from the total of 80 households through proportional allocations after employing purposive selection of the study sites. Primary data were gathered through a semi-structured questionnaire and face-to-face conversations. Descriptive statistics and Pearson's chi-square test were performed to examine respondents' characteristics, irrigation related perceptions, and association between usage of solar tube-well and perceived changes in level of agricultural production, respectively. About two-thirds (66.7%) of the respondents reported using solar tube wells in the area. Electric load shedding (40.4%) was the leading cause for switching over to solar pumping followed by high cost of diesel/electricity (29.8%). In general, 73.7% of the respondents reported an increase in crop production, 80.7% said irrigation cost was decreased significantly and 54.4% cultivated both wheat and maize. Solar tube-well use was strongly associated with reported improvement in productivity ($\chi^2 = 40.714$, $p < .001$). These results suggest substantial economic and production benefits from solar irrigation technology in the study area. Since the study was cross-sectional, based on a small purposively selected sample size and partially depended on self-reported outcomes, recommendations for wider adoption of the technology should be carefully considered. Expansion of solar irrigation should be coupled with affordable finance, technical assistance, high-efficiency irrigation and groundwater monitoring.

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Introduction

Agriculture in Pakistan is dependent on irrigation through water drawn from various sources, whereas water pumped from tube wells needs good and cheap sources of energy. The rising costs of electricity and fuels, in addition to irregular electricity supplies from the state, may raise costs and affect the schedule of pumping activities. Solar photovoltaic (PV) pumping technology utilizes solar energy to run water pumps with no fuel costs associated with the use of diesel generators. Internationally, solar pumping technology has been demonstrated to have the potential to offer reliable irrigation with benefits associated with food production and energy security through proper design and operation at the farm level (IRENA, 2016; IRENA & FAO, 2021).

The country has significant solar energy potential, as well as a substantial agricultural sector that relies heavily on groundwater use. According to a recent assessment, solar irrigation systems have the potential to reduce energy costs and enhance irrigation in far-off-grid regions in Pakistan, but adoption is hampered by a lack of technical know-how, maintenance resources, high capital costs, and institutional and policy barriers (Hussain et al., 2023). In addition, farmers may find it challenging to purchase PV irrigation systems with a large initial capital outlay. Evidence from Pakistan suggests that solar energy has the potential to impact a farmer's income. Khan et al. (2024) investigated the effect of solar-energy usage on farmers in Pakistan using a sample size of 1,080 crop farmers. The study found that solar energy has a positive effect on farmers' income while controlling for observed farm and farmer characteristics. In line with this, Raza et al. (2022) found that smallholder farmers in Punjab who used PV high-efficiency irrigation systems benefited significantly from substantial cost reduction, water saved, and increased farm income. This implies that the type of energy used in agricultural production could influence farm-level profits.

The study by Jan et al. (2020) among 520 sampled households in northwest Pakistan revealed the relevance of income, education, energy expenditure, access to markets, and information in the adoption of solar PV systems. In addition, a recent systematic review of solar irrigation in South Asia highlighted five key factors that hinder or promote solar irrigation adoption in the region: capital subsidies, low-cost technologies, water security, policy support, and agro-climatic conditions, with large capital costs, insufficient technical skills, and water-related hazards as constraints (Gupta & Singh, 2025). Therefore, the adoption of solar irrigation technology is complicated by various factors beyond farmers' control or requires them to acquire new skills regarding irrigation practices and water governance. District Karak is a semi-arid region with high summer temperatures and low but inconsistent rainfall, resulting in significant groundwater use for irrigation in some communities. Recent research in the region shows that groundwater is a critical resource that requires improved management practices due to water-quality and water-level hazards in the area (Muneer et al., 2025). Solar pumping systems can help provide energy access and reduce irrigation costs in the area. However, solar technology does not address the groundwater challenges and should not be promoted as a solution to groundwater overexploitation.

Although there is a wealth of local literature on solar irrigation, much of it pertains to national-level solar irrigation studies. This study focuses on District Karak, highlighting the relevance of solarized tube wells in the local context. Specifically, the study examines the agricultural benefits of solarized tube wells for farmers in Atti Khel and Painda Khel and determines their impact on the local economy. To achieve the objectives, the study describes the socio-economic characteristics of the respondents, identifies the motivations for adopting solar pumping technology, reports the changes in crop production and irrigation costs following the adoption, and evaluates the association between solar tube-well use and agricultural production.

The productivity of agriculture in arid areas is highly dependent on the availability of water for irrigation. Groundwater tube-well irrigation is an important agricultural practice in Pakistan, particularly in areas with insufficient surface-water resources. Traditional tube-well irrigation using diesel fuel or grid electricity is associated with large costs for farmers. Rising diesel prices, load shedding, and the lack of reliable electricity have driven farmers to invest in alternative energy sources, such as solar photovoltaic (PV) pumping systems. Ali et al. (2016) conducted a survey among 950 farmers in Punjab, Sindh, Khyber Pakhtunkhwa (KP), and Balochistan regarding the impact of alternative energy water pumps on wheat, rice, and maize yield and farmers' income. The researchers found that the adoption of alternative-energy water pumps had a significant positive impact on the crops and income. Education, wealth, access to credit, and loadshedding were found to be factors affecting the adoption of alternative-energy water pumps. The study suggests that the replacement of traditional energy sources with alternative ones can result in significant benefits to farmers in terms of energy saving and increased agricultural productivity.

Solar irrigation has since been studied extensively in Pakistan. Akbar et al. (2023) analyzed rice production, groundwater use, and energy use in Pakistan over forty years. The researchers concluded that irrigation with groundwater requires considerable amount of energy for pumping, especially when diesel fuel is used for tube wells. The researchers suggest that the conversion of existing electric and diesel tube wells into solar ones has a short payback period thanks to the high capital investment required. On the other hand, improvements in water productivity and the optimization of solar PV arrays can bring long-term benefits. The study highlights the significance of solar energy for agricultural irrigation in Pakistan, especially in terms of reducing energy expenditures.

The potential benefits of switching to solar irrigation were confirmed by Khattak et al. (2024) in a techno-economic and environmental analysis conducted in four sites in KP. The researchers evaluated the use of solar PV/diesel systems with and without grid connection and came to the conclusion that standalone solar PV systems could provide cost-effective irrigation with significantly reduced environmental impact. According to the researchers, the option of grid connection with the possibility to buy and sell electricity is most promising for the study area. The study is relevant to the current one because it shows that solar energy can be used to promote sustainable agricultural development in KP.

At the level of individual farmers, solar irrigation technology adoption depends on several factors. Khan et al. (2025) conducted a study in Balochistan analyzing the determinants of solar tube-well adoption among farmers. The researchers found that the solar PV adoption was positively associated with the respondents' level of education, years of experience, perception of groundwater availability, operating requirements, and cost-effectiveness. The availability of credit and the reduction of the initial investment were identified as key factors promoting solarization. This study shows that the adoption of solar irrigation technology is a complex process that goes beyond the mere availability of solar resources. It can be the basis for the current investigation into the relationship between solarized tube wells and agricultural productivity in District Karak.

Gul et al. (2025) made a similar discovery while studying the factors affecting the adoption of solar energy tube wells among 576 rice farmers in Sindh. The researchers used a Probit model to evaluate the effect of various socioeconomic variables on farmers' willingness to adopt solar irrigation. The study found that education, gender, innovativeness, internet use, farm diversification, credit accessibility, and location significantly predicted solar adoption. Farmers across all sites had an average adoption rate of 51.3%. The researchers recommended that improving access to credit, offering tax incentives, and distributing extension services would promote solarization in the study area. This finding is useful to the current study because it provides additional insight into the factors affecting farmers' attitudes towards solar irrigation.

The effect of solar irrigation on farmers' income has also been studied extensively at the individual level. Khan et al. (2024) investigated the association between the adoption of solar energy and crop-farmer income in Pakistan. The study used logit regression and propensity score-matching analysis on a sample of 1,080 crop growers. The researchers found that adopting solar energy had a positive effect on farmers' income. Education, farm size, agricultural extension, cooperatives, access to credit, and the availability of tube wells were found to be significant predictors of solar adoption and income. The study demonstrates that switching to solar irrigation can be beneficial to farmers not only in terms of reducing energy expenditures but also in terms of increasing income.

Soil salinity and waterlogging, however, are serious concerns regarding the promotion of solar irrigation in Pakistan. Jamil et al. (2025) studied the impact of switching from diesel to solar PV irrigation tube wells on groundwater levels and agricultural productivity in the Lower Indus Basin of Pakistan. Using a matched comparison between solar and diesel pump owners, the researchers found that the former extracted significantly more groundwater than the latter. Solar pump owners extracted on average 1.6 × 10 3 mm of groundwater compared to 1.3 × 10 3 mm for diesel pump owners. More than 75 percent of comparisons showed that solar pump owners extracted more groundwater. This study highlights the fact that solar irrigation can aggravate groundwater depletion in agricultural areas regardless of switching to a clean energy source.

This finding was corroborated by Gupta (2019), who studied the impact of solar irrigation on groundwater use in Rajasthan, India. The researcher used a difference-in-difference approach and a sample of 414 farmers in six districts to evaluate the effect of switching to solar pumps on diesel

use, electricity use, cropping intensity, and farming profits. Solar irrigation was found to reduce diesel and electricity use while increasing cropping intensity and profits in some districts. Annual profits increased by approximately 31–76 percent for solar pump adopters depending on the district. Despite the benefits, solar irrigation led to rising groundwater levels in all districts. The study shows that solar irrigation can affect the profitability of farms as well as the local hydrogeology depending on the region and agricultural practices.

Narayanamoorthy et al. (2025) conducted a similar field study in Tamil Nadu, southern India, comparing the performance of 152 solar pump owners with that of 152 electric pump owners. The researchers found that solar pump owners increased the extent of irrigated and cultivated land by a considerable margin compared to electric pump owners. The cropping intensity rose from roughly 100% to 210% on average. Moreover, the annual net farm income per crop was higher for solar pump owners compared to electric pump owners. The researchers concluded that farms using solar irrigation had a higher crop yield and lower cultivation costs than those using electric pumps. The study is particularly relevant to the current one since it used quantitative methods to compare the benefits of solar irrigation for farms.

Solar irrigation has also been studied in terms of its technical and environmental performance in Assam, India. Terang and Baruah (2023) evaluated the comparative advantages of solar PV, diesel, and electric water-pumping systems for agricultural use in Assam. The researchers recommend that solar PV pumping systems should be promoted in Assam due to their potential to reduce operating costs and greenhouse gas emissions. They also note that the viability of solar irrigation depends on several factors, including groundwater availability, cropping patterns, energy prices, and financial incentives. This study is significant because it helps understand the role of solar irrigation in agricultural development in a region with a hydrogeology and climate similar to those in KP.

The economic feasibility of solar irrigation has been demonstrated in Nepal as well. Karki and Lohani (2020) conducted a techno-economic analysis of solar water pumping for irrigation in Nepal and found that it had a benefit–cost ratio (BCR) of 1.6 and an internal rate of return (IRR) of 18.15%. The study shows that solar water pumping can be a lucrative investment, particularly in remote areas, where connecting to the electric grid is too expensive. Solar irrigation was found to be economically viable for relatively small areas of land. This study highlights the potential benefits of solar irrigation for farmers in rural KP, who do not have access to the electric grid.

A recent study conducted in KP is particularly relevant to the current one. Muhammad (2025) evaluated the impact of the solarization of 54 tube wells carried out by the Directorate General of Agricultural Engineering, KP, in the Kurram District. The study contains valuable information regarding the changes in water-table depth, discharge, and crop yield before and after solarization. This empirical study serves as a useful basis for the current one since it provides detailed evidence on the benefits of solar irrigation in KP.

Materials and Methods

Study area

This study was conducted in District Karak, Khyber Pakhtunkhwa, with field activities focusing on Atti Khel, and Painda Khel villages in Takht-e-Nasrati Tehsil. According to the source paper, Karak is a semi-arid agricultural district where groundwater and tube wells play an essential role in crop production. District Karak consists of three tehsils and 23 union councils. The study area is considered to have a water-energy nexus because of the reliance on groundwater and electricity for irrigation purposes.

Study design and sampling

The study adopted a cross-sectional survey design to gather information on the association between the use of solar tube wells and agricultural production. Takht-e-Nasrati Tehsil was selected in the District Karak from the three tehsils. One union council and two villages were conveniently selected from the tehsil for the study. Altogether, the two villages were selected A purposive sampling technique was used as a total 57 households were selected. These households had extensive experience in farming in this arid land area. Using proportional allocation, 33 respondents were selected from Atti Khel and 24 respondents from Painda Khel. Since the selection of the villages and the union council was convenience-based, the sample does not represent all farmers in District Karak but only those farmers in the study villages. The data collected were primary data obtained from the respondents through a semi-structured questionnaire and face-to-face interviews. The questionnaire sought to obtain information on the socio-economic characteristics of the respondents, use of solar tube wells, reasons for adoption, crop production, irrigation cost, and perception on the effect of solar tube-wells on crop production. According to the source paper, the questionnaire was designed in English and administered to the respondents in Pashto. The ethical approval number for the study is missing in the source paper. It is recommended that the researchers add the appropriate ethics approval and informed-consent statements if the required approvals were obtained.

Statistical analysis

The statistical analysis was performed in Statistical Package for the Social Sciences (SPSS). Frequency analysis was done to determine the prevalence of certain responses to topical questions. Pearson's chi-square analysis was done to establish an association between solar PV use and the reported changes in agricultural production at $\alpha = .05$. The analysis was explicated as an association test since the study was cross-sectional and the response variable was self-reported by the respondents.

Results and Discussions

Respondent characteristics

The study consisted of 57 respondents, of whom 33 (57.9%) were from Atti Khel and 24 (42.1%) were from Painda Khel. The largest age group was 41–50 years (40.4%), followed by 31–40 years (24.6%) and more than 50 years (24.6%); 20–30-year-old respondents made up 10.5%. Most respondents were literate, and 42.1% were reported to have higher education or above. Household size was most commonly 3–6 members (45.6%), followed by 7–9 members (40.4%). Landholding was generally small: 38.6% reported less than 5 acres, 36.8% reported 6–10 acres, and 24.6% reported more than 10 acres.

Table 1. Selected characteristics of the sampled households.

Characteristic	Category	n	%
Village	Atti Khel	33	57.9
	Painda Khel	24	42.1
Age	20–30 years	6	10.5
	31–40 years	14	24.6
	41–50 years	23	40.4
	>50 years	14	24.6
Household size	3–6 members	26	45.6
	7–9 members	23	40.4
	10–12 members	7	12.3
	≥13 members	1	1.8
Landholding	<5 acres	22	38.6
	6–10 acres	21	36.8
	>10 acres	14	24.6

Data Source: Field Survey DATA 2025

Adoption and reasons for solar tube-well use

Overall, 38 respondents (66.7%) were reported to use solar tube wells for agricultural irrigation, while 19 (33.3%) said they did not. The most frequently reported reason for switching to solar pumping was electric load shedding (40.4%), followed by high diesel or electricity cost (29.8%), environmental sustainability (17.5%), and government subsidies or support (12.3%). The results suggest that energy reliability and cost of operation were more immediate motivations than environmental considerations alone.

Table 2. Main reasons reported for shifting to solar-powered tube wells.

Reason for shifting to solar tube well	n	%
Electric load shedding	23	40.4
High diesel/electricity cost	17	29.8

Environmental sustainability	10	17.5
Government subsidies/support	7	12.3
Total	57	100.0

Data Source: Field Survey DATA 2025

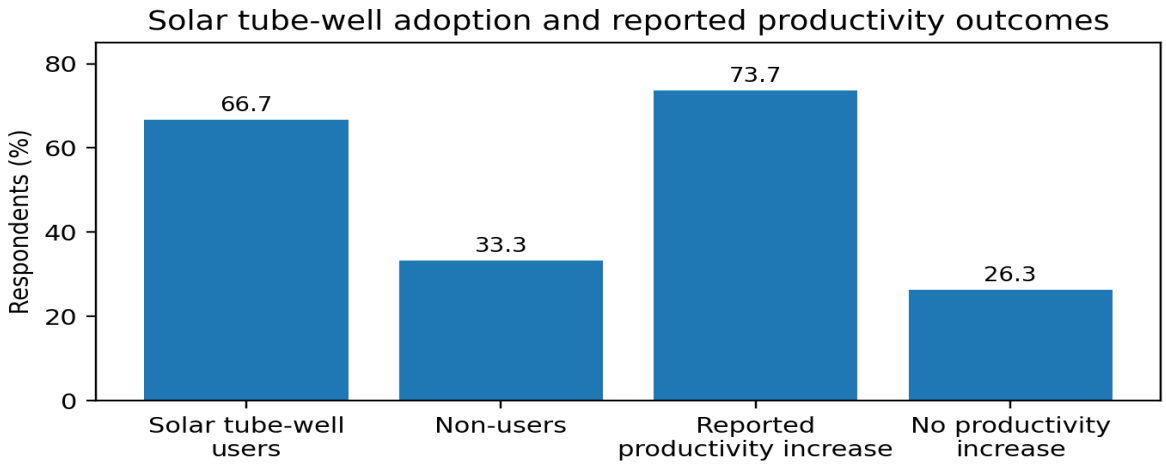


Figure 1. Solar tube-well adoption and reported agricultural productivity outcomes.

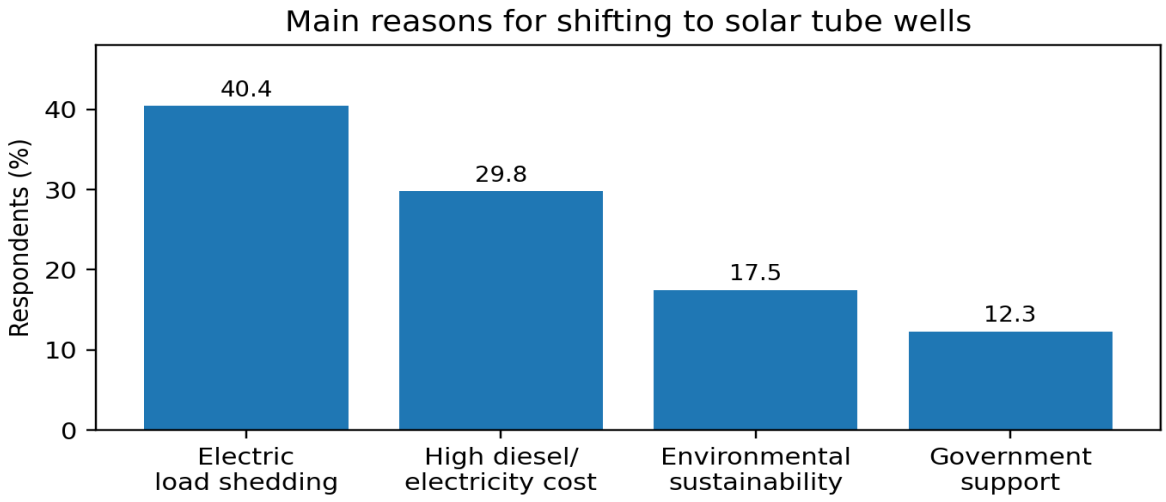


Figure 2. Main reasons reported for shifting to solar tube wells.

Crop production and irrigation-cost outcomes

A total of 42 respondents (73.7%) were reported to see an increase in crop production after adopting solar-powered irrigation, whereas 15 (26.3%) said there was no increase. Among

the crops reported in the study area, wheat and maize were the main crops. Wheat alone was reported by 40.4% of respondents, maize alone by 5.3%, and wheat and maize together by 54.4%. With respect to irrigation expenditures, 46 respondents (80.7%) said that these were greatly reduced, and 11 (19.3%) said that the costs were slightly reduced. These responses suggest a strong perceived economic benefit from solar pumping. Beyond productivity gains, literature highlights the broader socio-economic impacts of solar irrigation technologies. Farmers benefit from reduced input costs and increased profitability, while communities experience improved resilience against energy crises and environmental challenges (Ahmad & Nabi, 2022). The adoption of solarized tube wells also encourages crop diversification and sustainable farming practices, which are essential for long-term rural development. However, challenges such as high installation costs, limited technical expertise, and maintenance requirements remain barriers to widespread adoption. Scholars argue that government subsidies, institutional support, and farmer training programs are critical to overcoming these hurdles and ensuring that solarized tube wells serve as a catalyst for sustainable agricultural development in Khyber Pakhtunkhwa (Khan & Ullah, 2021; Ahmad & Nabi, 2022).

Table 3. Reported production, crop, and irrigation-cost outcomes.

Outcome	Category	n	%
Crop production	Increase	42	73.7
	No increase	15	26.3
Main crops	Wheat only	23	40.4
	Maize only	3	5.3
	Wheat + maize	31	54.4
Irrigation cost	Greatly reduced	46	80.7
	Slightly reduced	11	19.3

Data Source: Field Survey DATA 2025

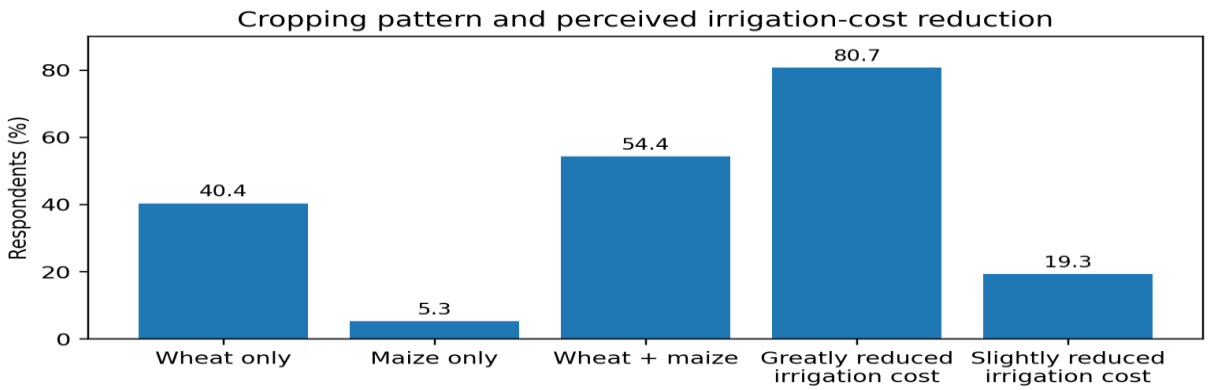


Figure 3. Cropping pattern and perceived irrigation-cost reduction.

Association between solar tube-well use and agricultural productivity

The cross-tabulation revealed that all 38 solar tube-well users reported increased agricultural productivity, whereas 4 of the 19 non-users reported increased productivity and 15 reported no change. Pearson's chi-square test showed a statistically significant association between solar tube-well use and reported change in agricultural productivity ($\chi^2 = 40.714$, $p < .001$). The strength and direction of this pattern are consistent with the descriptive finding that solar users were substantially more likely to report improved production. Nonetheless, the association should not be interpreted as proof that solarization alone was responsible for the productivity increase because the groups may differ in farm size, inputs, land quality, irrigation intensity, wealth, and other unmeasured characteristics. Solarized agricultural tube wells are increasingly recognized as a transformative solution for rural irrigation, particularly in water-stressed regions like District Karak. Traditional diesel-powered tube wells have long been associated with high operational costs, fuel shortages, and environmental degradation. Research shows that solar-powered irrigation systems significantly reduce energy expenses while ensuring reliable water supply for crops, thereby enhancing agricultural productivity (Khan & Ullah, 2021). By replacing fossil fuel dependency with renewable energy, solarized tube wells contribute to climate change mitigation and align with sustainable development goals (FAO, 2020). In Karak, where groundwater is the primary source of irrigation, solarization offers farmers a cost-effective and environmentally friendly alternative that directly supports food security and rural livelihoods (Qureshi & Ashraf, 2019).

Table 4. Association between solar tube-well use and reported change in agricultural productivity.

Solar tube-well use	Productivity increased n (%)	No change n (%)	Total
Yes	38 (66.7)	0 (0.0)	38 (66.7)
No	4 (7.0)	15 (26.3)	19 (33.3)
Total	42 (73.7)	15 (26.3)	57 (100.0)

Data Source: Field Survey DATA 2025

The present study offers localized evidence that solar-powered tube wells are favorably regarded by many farmers in the study villages. Two-thirds of respondents used solar tube wells, and the primary motivations were electricity load shedding and high conventional energy costs. This finding aligns with the broader Pakistani writing on solar irrigation, which identifies unreliable electricity and high energy costs for pumping as important drivers of adoption (Hussain et al., 2023; Khan et al., 2024). The study also concurs with evidence of reduced costs and reliable water supply as important factors driving solar irrigation adoption in South Asia (Gupta & Singh, 2025).

The reported reduction in irrigation costs is one of the strongest claims of the study: 80.7% of respondents described it as substantial. This finding can be rationalized due to the elimination or substantial reduction in recurring diesel consumption and dependence on the grid for electricity. In Punjab, Raza et al. (2022) report that PV-powered high-

efficient irrigation systems lowered operational costs and yielded major socioeconomic gains. IRENA (2016) also highlights reduced fossil-fuel expenditure and reliable decentralized irrigation as advantages of solar-powered pumping. However, the economic benefit should be considered over the life time, as the initial capital, battery or inverter replacement if applicable, pump maintenance, and downtime can significantly change profitability.

The observed production response was also large, with 73.7% of households reporting an improved production, and all solar users in the cross tabulation reporting an increase. The modality is likely improved access to irrigation water at critical crop stages, particularly where conventional pumping is impeded by electricity shortages or high fuel costs: reliable irrigation can enable more timely planting, reduce crop-water stress, allow crop diversification. The finding that more than half of respondents reported growing both wheat and maize is in line with this understanding, although the current survey did not measure actual yield per hectare, irrigation frequency, or water volume.

The significant chi square result bolsters the evidence on the association of solarization and perceived productivity improvements within the sample (however, it is important to differentiate association from causation: the study did not utilize a randomized intervention, did not measure crop yields or a matched comparison group, and solar adopters may have had larger farms, better access to credit or better groundwater. Khan et al. (2024) address the selection issues by using propensity-score matching and found positive income effects of solar adoption, showcasing the value of more rigorous approaches in local studies).

One of the main sustainability concern is groundwater management: solar pumping may reduce the marginal cost of pumping water, which is advantageous to farmers but can also promote increased pumping. Hussain et al. (2023) explicitly highlight groundwater exploitation as a risk of solar irrigation in Pakistan, while Gupta and Singh (2025) emphasize that solar irrigation should be combined with groundwater governance. This is a particular concern in Karak as recent hydrogeological research highlights vulnerability and stressing groundwater (Muneer et al., 2025). Hence, the policy aim should not be to maximize the number of solar pumps but to promote solar energy coupled with efficient irrigation, metering or monitoring if possible, crop planning, and local groundwater management.

The study also has implications on the policy on social and institutional aspects: one third respondents were not using solar tube wells, raising questions as to the barriers despite the reported benefits. Literature identifies upfront cost, financing constraints, awareness, technical expertise, after-sales service, policy uncertainty as persistent challenges (Jan et al., 2020; Hussain et al., 2023; Gupta & Singh, 2025). For the smallholders in Karak, financing mechanisms and technical support may be as important as the availability of solar radiation. Subsidies should be designed to promote access for financially constrained farmers and link support with efficient irrigation and groundwater use.

Overall, the study endorses solarized tube wells as a promising component of the local energy policy, but not a standalone solution. The best policy option is likely a combination of solar

pumping, high-efficient irrigation technologies, farmer training, preventive maintenance, affordable credit, groundwater monitoring, and crop-water management. This would preserve the economic advantage of solar energy while mitigating the risk that cheaper pumping speeds up exploitation of groundwater.

Conclusions

The study found that solarized agricultural tube wells were widely adopted among the surveyed households in Atti Khel and Painda Khel, with 66.7% reporting the use. Electric load shedding and high diesel/electricity costs were the leading reasons for adoption. Most respondents reported low irrigation costs and nearly three quarters reported increased crop production. Solar tube well use was significantly associated with reported productivity improvement ($\chi^2 = 40.714$, $p < .001$). The findings therefore show a strong perceived contribution of solar irrigation on farm production and irrigation-cost reduction in the study villages.

Moreover, the study does not establish a causal yield effect due to its cross-sectional design, small purposively selected sample, and reliance on self-reported outcomes. Hence, future studies should measure crop yields before and after solarization and irrigation water volume, pumping hours, system capital and maintenance costs, groundwater levels, and household income, ideal with larger and randomly selected samples. It is recommended that expand access to affordable solar-irrigation finance for small and medium farmers through targeted subsidies or concessional credit, or cost-sharing mechanisms while avoiding subsidy structures that encourage excessive groundwater abstraction.

Link solarization programmes to high-efficiency irrigation systems to convert energy savings into water savings rather than simply increasing pumping. Establish farmer training and local technical-support arrangements for system sizing, operation, cleaning, pump maintenance, inverter/controller troubleshooting, and timely replacement of components. Develop groundwater monitoring and water-management rules in areas where solar pumping is expanded. Solarization should be accompanied by water-use planning, particularly for water-intensive crops. Strengthen agricultural extension services so that farmers receive information on crop-water requirements, irrigation scheduling, soil-moisture management, and the economic payback of solar systems. Future evaluations should use measured crop yields, irrigation water volumes, farm income, total system costs, and groundwater indicators rather than relying only on perceptions. A larger multi-village study across the three tehsils of Karak would improve generalizability.

Study Limitations

The main limitations are small sample size ($n = 57$), purposive selection of the study locations, cross-sectional design, and reliance on self-reported changes in productivity and costs. The analysis did not control for confounding factors as farm size, soil quality, fertilizer use, improved seed, rainfall, irrigation frequency, groundwater depth, access to extension and credit. Additionally, actual crop yields and water extraction volumes were not measured. These limitations restrict causal interpretation and generalization beyond the study villages.

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