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The Socio-Economic Impact of Using Photovoltaic (PV) Energy for High-Efficiency Irrigation Systems: A Case Study

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Abstract: This paper presents the results of a field study undertaken all over the Punjab, Pakistan, to evaluate the socio-economic and climatic impact of photovoltaic-operated high-efficiency irrigation systems (HEIS), i.e., drip and sprinkler irrigation systems. Nearly half of the rural population relies on agriculture for a living, and the recent energy crisis has had a negative impact on rural communities. Farmers' reliance on fossil fuels for the operation of irrigation systems has increased exponentially, resulting in the high costs of agricultural production. Primary data regarding on-farm agriculture and irrigation practices used in this study were collected through an intensive on-farm survey, while secondary data were taken from published reports and statistics. The results of the current investigation show that the installation of PV systems has resulted in the increased adoption of high-efficiency irrigation systems, a reduction in the high operational costs incurred on account of old diesel-powered pumping systems (with an annual saving of 6.6 million liters of diesel), a 100% increase in farmer's income, a reduction of 17,622 tons of CO_2 emissions per annum, and 41% savings in water. The unit cost of PV-powered HEIS was found to be 0.1219 USD/kWh, which was 4% and 66% less than subsidized electricity cost and diesel cost, respectively.

Keywords: photovoltaic systems; high-efficiency irrigation systems; energy saving; climate smart agriculture; water conservation

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1. Introduction

Agriculture is essential for the growth of many countries around the world. It is important to adopt methodologies and technologies to assist agriculture in providing food that is sufficient for the entire population [1]. According to past experiences, irrigation should be addressed in the context of a multidisciplinary strategy that covers the energy, water systems, and food nexus. In fact, energy, water, and food are all interlinked valuable resources that require strategies and technologies that can promote sustainable management and efficient use [2]. The agricultural sector can be a source of renewable energy, such as biomass or biofuels, but can also make a significant contribution to reducing the environmental impact of energy use by utilizing sustainable energy sources [3]. In fact, research conducted by [4] sought to find out the social and economic implications of shifting fossil irrigation to renewable energy sources in India. In addition, the study examines the politically imposed barriers to the solar boom in the agricultural sector. Another study on the relationship between agriculture and energy was conducted in [5], to understand the economic viability of solar photovoltaic water pumping systems. Similar research [6] was conducted in China, focusing on the benefits of photovoltaic (PV) water pumping technology and the relationship between customer profiles and system operation.

The agriculture sector employs a large number of people and contributes significantly to GDP [7]. Punjab's agriculture contributes about a quarter to the provincial gross domestic product (GDP), and employs, directly or indirectly, about a half of the provincial manpower. It also contributes to 8% of the country's food requirements. During recent energy crises in Pakistan, rural communities in the general and agriculture sector in particular have faced severe electricity shortfall of more than 3000 h annually [8]. Energy requirements for water pumping in agriculture are mainly met by using diesel engines and prime movers. Use of diesel significantly increases the costs of agriculture production, and the emission of greenhouse gases contributes to the risk of climate change [9]. The Punjab Growth Strategy 2018 [8] envisaged "better use of energy in agriculture" and provided means of harnessing renewable energy to supplement conventional energy sources which are limited and expensive. These issues can be addressed by replacing fossil fuels with renewable energy resources and changing the irrigation methods from conventional to conservative and efficient irrigation. There is a huge scope for improving productivity at the farm level through the adoption of modern and productive technologies for the optimal use of inputs, particularly water, energy and fertilizers. Pakistan is spending around 14 billion USD annually to import fuels, out of which 20% goes to the agriculture sector. One fifth of total energy, electricity and fuels, is consumed in irrigation [10].

Pakistan has one of the best canal irrigation systems in the world, but there is still a shortage of water throughout the country. The annual average rainfall is less than the overall crop water demand, so the canal water and rainwater are insufficient to meet the irrigation needs of the agricultural sector. To tackle the water scarcity problem, the country has installed more than one million tube wells, of which the majority are diesel-operated [11], and around 0.13 million agriculture pumps in the Punjab are connected to the electric grid [12]. In Pakistan, water shortage is a huge challenge. At the same time, the inefficiency of the irrigation system leads to the wastage of water resources, which ultimately leads to a decline in crop water productivity [13,14].

Photovoltaic energy generation systems reduce the dependence on fossil fuels [15,16]. Photovoltaic power tends to be the most cost-effective option, as daylight is available for more than 310.0 days a year. Photovoltaic energy generation systems are not only eco-friendly, but they also need little maintenance and have no fuel costs [17]. An increasing number of photovoltaic energy generation systems have the potential to minimize the emissions of greenhouse gases (GHGs) associated with energy generation [18]. Although people are more and more interested in exploring the characteristics and prospects of PV energy generation projects, less attention has been paid to the social material and infrastructure arrangements that support these bottom-up energy generation projects [19].

Hundreds of millions of agricultural families live in remote areas and still have no access to electricity. Lack of access to electricity affects the socio-economic condition of rural agricultural families. PV energy generation systems, in the form of targeted social support programs and technical solutions, can promote energy access to rural agricultural families [20]. Providing rural societies with reliable energy services, mitigating climate change, and eliminating energy poverty are key infrastructure components. More decentralized energy solutions and a shift in the energy infrastructure paradigm are required for both low-carbon challenges and energy access [21]. Photovoltaic power in agriculture will also help to conserve energy, minimize grid power usage, and foster socio-economic growth [22,23]. Photovoltaic power is also more cost-effective than a conventional diesel irrigation system, which provides farmers in remote areas with cheaper access to water and improves their socio-economic and living conditions [24,25]. Research works [26,27] have investigated the socio-economic and environmental effects of using photovoltaic-operated high-efficiency irrigation systems on drip irrigation owners. The results showed that photovoltaic-powered high-efficiency irrigation systems have a major effect on resource savings, such as energy savings, labor cost savings, and water usage reduction, as well as improving crop yields and farmer benefits, all of which help to improve the quality of life in rural areas.

Photovoltaic-powered irrigation systems save labor and fuel cost in rural off-grid areas [28,29]. According to the research of López-Luque, R. et al. [30], less than 1.0 kW of power is needed to irrigate 1.0 hectare of agriculture land, and in scenarios where energy systems require less than 5.0 kW, DC motors are preferred and recommended over AC motors. Positive displacement pumps have been shown to be useful for higher heads, whereas diaphragm pumps are better for lower heads, both delivering above 70.0% efficiency [31–33]. In the arid zone of Punjab, Pakistan, research was conducted with the goal of installing and evaluating a solar-powered drip irrigation system. The system's performance, efficiency, and distribution uniformity were assessed. An economic analysis was also conducted to compare the solar-powered drip irrigation system to the diesel-powered drip irrigation system. The results showed that the PV-powered irrigation system was highly efficient and more economical. The PV-powered irrigation system also had very low operating costs compared with the irrigation system powered by a diesel engine [34].

Williamson, E. [35] used a photovoltaic-powered automated pumping system that allowed for automatic irrigation scheduling and water level control. The drip portion of the irrigation system ensured precise water application, reducing water loss due to wind and evaporation. Lower electricity operating costs and water savings were its long-term benefits. Pande, P.C. et al. [36] designed photovoltaic-powered high-efficiency irrigation systems for growing orchards in the arid region, taking into account various design parameters such as water pump capacity and specifications, diurnal variation in the water pump pressure due to irradiation changes, and compensation for water pressure in the drippers. Solar irrigation technology has developed and progressed tremendously in the past decade, and is used by farmers on agricultural lands in Sub-Saharan Africa. In terms of the reduction in greenhouse gases and payback periods, this technology can replace diesel-powered irrigation systems [37]. Another study considered the feasibility analysis of solar drip irrigation pumps in India. In India, agriculturists use photovoltaic energy to power the current diesel pumps and submersible pumps. The study concluded that these photovoltaic systems combined with drip irrigation systems could help increase crop yields, save water, and minimize expenditure on fertilizers and other agricultural inputs. In general, increasing production will help increase farmers' net income [38]. Photovoltaic (PV) water pumping will be beneficial for irrigation purposes and have a positive impact [39,40].

Pakistan, being located on the solar belt, has high solar irradiation ranging between 5 to 7 kWh per square meter per day that can generate 2.9 million MW. However, unfortunately, Pakistan is 27th with respect to total added PV capacity in the world, having a total installed power of 1600 MW, despite the excellent available irradiance.

The government of Punjab launched a subsidy scheme in 2016–2017 for the installation of PV systems to operate high-efficiency irrigation systems: drip and sprinkler systems on a cost sharing basis. The farmers shared 20% of the cost of PV systems and the government shared the rest. The PV HEIS system consisted of two parts, i.e., the PV system and HEIS. The PV system included PV array, variable frequency drive and the controlling unit (AC/DC breakers, etc.). The HEIS system included the electric motor, water pump, filtration system, venturi, control valves, mainline, sub-mains and laterals. The objective of the current study was to assess and evaluate the impact of the photovoltaic (PV)-operating high-efficiency irrigation systems (HEIS) throughout Punjab, Pakistan. The study may be regarded as base information for farmers, services and supply companies (SSCs), as well as researchers and decision makers all over the world regarding PV-operated systems and HEIS impacts on farmers' economy and the environment.

2. Materials and Methods

2.1. Study Area

Agricultural farms throughout the Punjab province were selected, as the study aimed to represent the impact of PV-operating HEIS throughout Punjab. During last three years, more than 2100 PV systems have been installed throughout the Punjab province under the subsidy scheme, as shown in Figure 1.

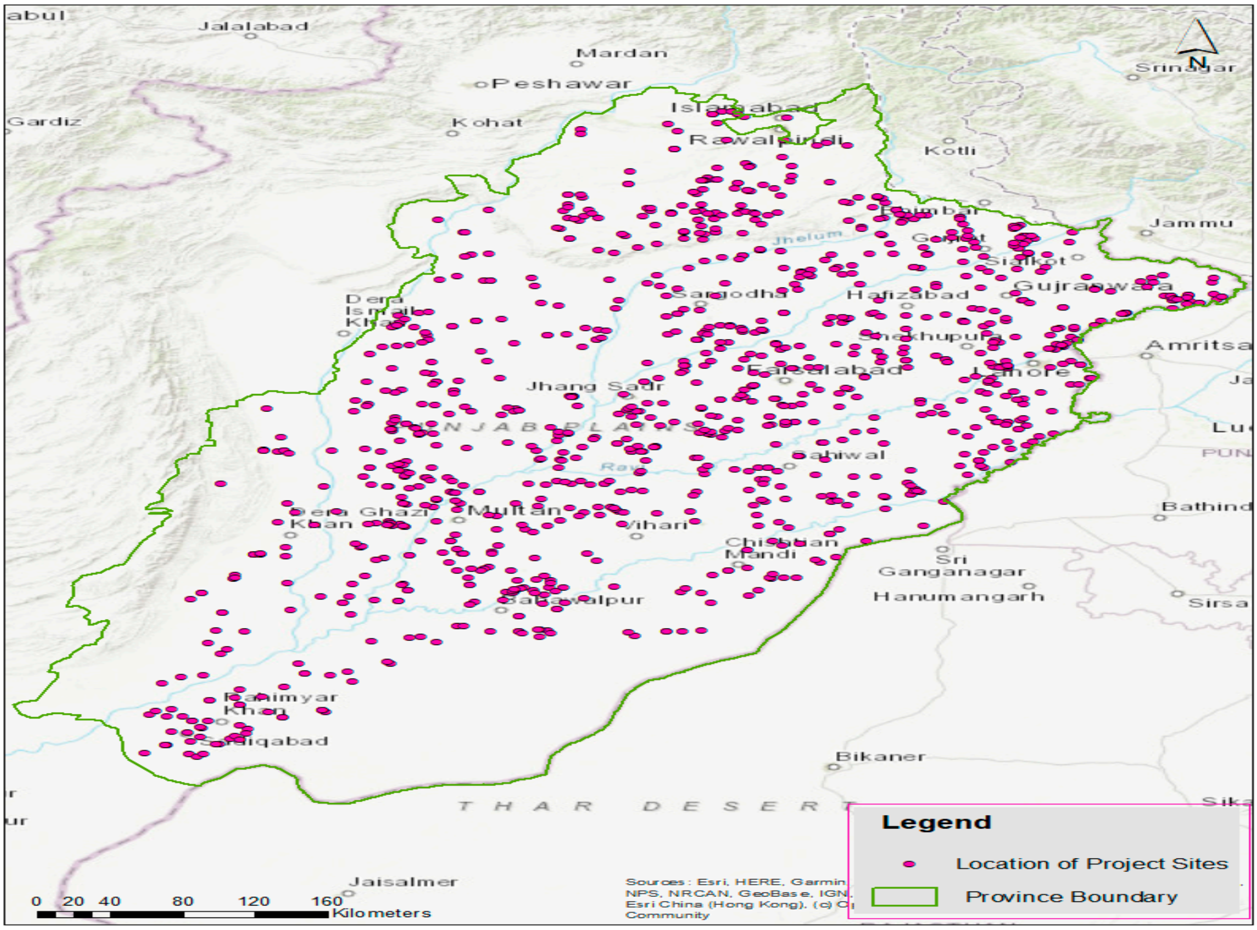

Figure 1. PV and HEIS project sites.

A total of 84 sample farms were surveyed and categorized as following:

1. Farms using PV-powered HEIS;
2. Farms using diesel- or electricity-powered HEIS;
3. Farms practicing flood irrigation were considered as a base case.

In this study, farms older than one-year were surveyed to obtain consistent data during the survey. Table 1 shows district-wise number of surveyed farms.

Table 1. District-wise number of surveyed farms.

District	HEIS Irrigated Farms	Flood Irrigated Farms	Total Farms
Lahore	2	1	3
Sheikhupura	0	2	2
Kasur	2	4	6
Nankana	2	0	2
Gujranwala	2	2	4
Sialkot	1	0	1
Faisalabad	2	2	4
T.T Singh	3	0	3
Rawalpindi	7	0	7
Chakwal	2	2	4
Attock	3	0	3
Mianwali	3	0	3
Bhakkar	3	0	3
Layyah	2	0	2
D.G. Khan	5	1	6
Bahawalpur	9	4	13
Bhawalnagar	1	0	1
Chiniot	1	0	1
Multan	1	0	1
Khanewal	2	5	7
Sargodha	1	1	2
Vehari	1	0	1
Lodhran	5	0	5
Total	60	24	84

2.2. Data Collection

A questionnaire comprising details of the farms, i.e., landholding, cropping pattern, irrigation practices, sources of energy and water, input costs, and revenues, was developed and used to fill in the primary data during the survey. An intensive on-site survey was conducted for the collection of data from 84 farms throughout the province. Tables 2 and 3 show the details of the surveyed farms.

The survey data show that the farmers with small to medium landholdings were growing high-value crops, and therefore preferred HEIS for precision in irrigation. The secondary data was taken from published reports and statistics, consulting engineer's reports and documents from the On-Farm Water Management (OFWM) department.

Table 2. Details of flood irrigation farms.

Description	Diesel-Operated Pumps	Electric-Operated Pumps	Canal-Irrigated	Total
No. of farms	11	12	1	24
Area under study (Acres)	726.0	523	14.0	1263
Orchard area (Acres)	15.0	73.0	0.0	88
Row and conventional crops area (Acres)	711.0	450	14.0	1175
Total farmer's holding (Acres)	1462.5	945.0	18.0	2425

Table 3. Details of HEIS farms.

Description	Diesel-Operated HEIS	Electricity-Operated HEIS	PV-Operated HEIS	Total
No. of farms	14	8	38	60
Area under study (Acres)	134.8	86.1	341.5	562
Orchard area (Acres)	54.5	19.9	114.1	188
Row crops area (Acres)	80.5	66.2	227.4	374
Total farmer's holding (Acres)	346.5	571.7	1450.2	2367

2.3. Data Analysis

The data collected from the survey were analyzed to present the results in this study. It was found that out of 84 farms, 24 farms were practicing conventional flood irrigation. Only 1 out of these 24 farms had enough canal water available throughout the year to meet the irrigation requirements: 11 farms were using diesel, and 12 were using electricity to pump groundwater for flood irrigation. Moreover, 1175 acres out of the 1263 acres under study were used for growing conventional crops, and only 88 acres were covered with orchards.

On the other hand, 60 farms were practicing HEIS irrigation on an area of 562 acres. Eight out of these 60 farms had an electric grid available for operating HEIS, 14 were using diesel, and 38 were using PV-powered HEIS. It was observed that most of them were growing high-value vegetables on 374 acres, and 188 acres were covered with orchards.

The average size of the farms under the PV system intervention was found to be 10 acres. The average capacity of installed PV systems was 9 kWp to match the horsepower of installed pumps with an average of 8.5 HP. The cost of the PV system per acre was calculated as 953.33 USD, on average, whilst per kWp cost was found to be 1000 USD. The initial cost of PV systems was relatively higher, but low operational cost made it a feasible solution to be adopted by the farmers. Table 4 shows the details of the PV system interventions.

Table 4. Details of PV System interventions.

PV Intervention—Site Details	Average Nos.
Area of farms (acres)	10.10
Horsepower of pumps (HP)	8.50
PV systems power (kWp)	9.00
PV systems cost (USD)	8733.33
PV cost per acre (USD)	953.33
PV cost per kW (USD)	1000

3. Results and Discussion

3.1. PV-Powered HEIS Adoptability

The government has long been putting effort into promoting HEIS in Punjab; however, the success rate has not been convincing. For example, from 2011 to 2016, an area of about 20×10^3 acres was brought into HEIS, as shown in Figure 2. The high operational costs of HEIS were identified as one of the main constraints for its adoptability and sustainability, particularly those which were powered by diesel. However, after the intervention of PV coupling with HEIS, adoptability was accelerated and 20×10^3 acres were brought under HEIS within only two years.

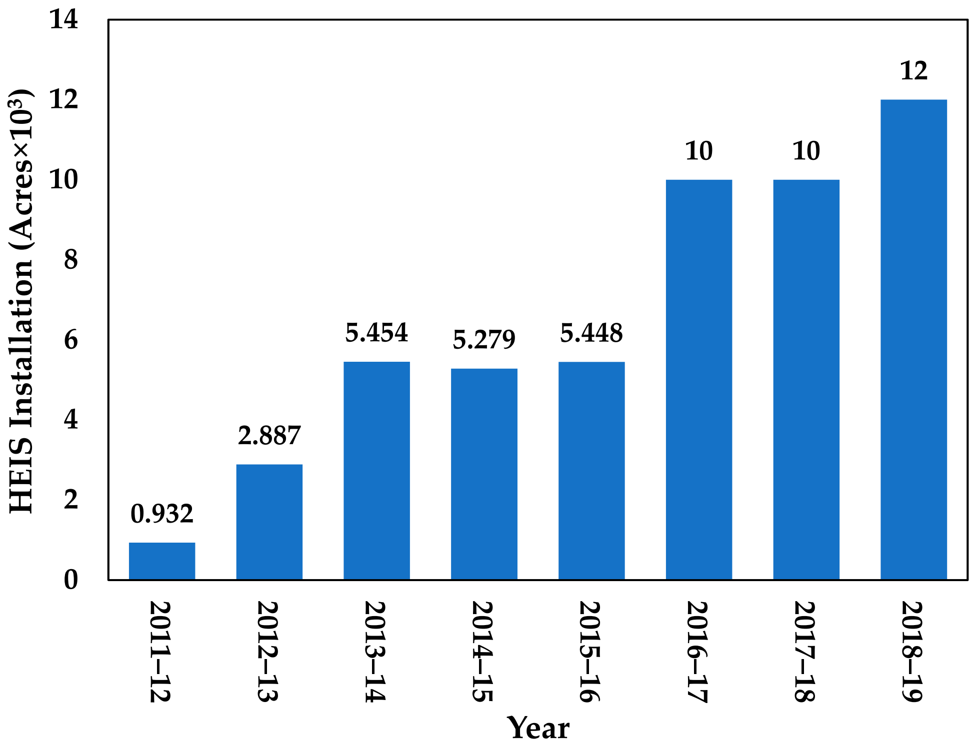

Figure 2. Year-wise adoptability of HEIS before and after PV system interventions.

Moreover, it was found that 53 out of 84 farms had grid connection available in their vicinity. This was also evident from the analysis that 38 farms adopted HEIS after it was offered with PV, compared with 14 farmers operating HEIS with diesel.

3.2. Savings in Energy Cost

The survey data was analyzed to quantify the consumption of diesel for operating HEIS and flood irrigation. The analysis revealed that average annual diesel consumption was 330 L per acre and 731 L per acre, for operating HEIS and flood irrigation, respectively. Table 5 shows that HEIS irrigation consumes 55% less diesel compared with flood irrigation.

Table 5. Diesel consumption for HEIS and flood irrigation.

Description	Flood Irrigation Farms	HEIS Irrigation Farms
Average diesel consumption per acre per annum (Liters)	731	330
%age difference	-	55%

At a national level, it is important to reduce fuel dependence and enhance the prospects of rural development by improving access to energy and water. The agriculture sector is consuming energy of above 200,000 tons of oil equivalent (TOE) in the form of petroleum products, and almost 500,000 TOEs in the form of electricity.

At farm level, photovoltaic energy generation technology can provide a reliable and cheap energy source for pumping irrigation water in remote rural areas, especially in areas those are not connected to the national electric grid, or where a consistent supply of liquid fuels (diesel or petrol) and maintenance services are not guaranteed. The current economic situation of the country demands clean and low-cost (operating) technologies that can reduce national dependency on fuel imports. Therefore, the shift to PV systems can considerably reduce the fuel import bill.

PV systems with a capacity of 17.29 MWp were installed to operate HEIS at around 20×10^3 acres under this subsidy project, resulting in an annual saving of 6.6 million liters of diesel. This saving in fuel corresponds to a saving of 4.84 million USD per annum in import bills of diesel. A cost comparison for the 7.46 kW pumping systems powered by solar, diesel and electricity was performed. The unit cost of PV-powered HEIS was found to be 0.1219 USD/kWh, which was 4% and 66% less than the subsidized electricity cost and diesel cost, respectively, as shown in Figure 3. This saving in energy cost is similar to those found in the studies conducted by Mongat, A.S. et al. [34] and Tamoor, M. et al. [26].

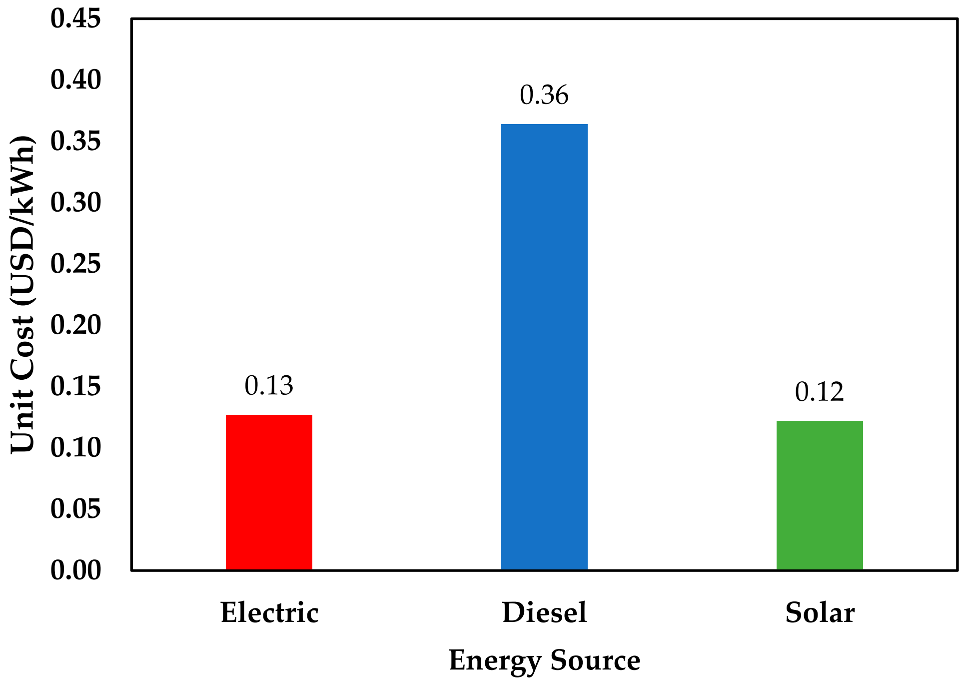

Figure 3. Unit cost of electric-, diesel- and PV-powered pumping system of 7.46 kW.

3.3. Foreign Exchange Savings (Reduction in Diesel Inputs)

The annual diesel consumption for irrigating an acre with HEIS was found to be 330 L, which can be saved with solar-powered HEIS. This would result in annual savings of 6.6 million liters of diesel, from around 20 $\times$ 10^3 acres, under the subsidy project. This saving in fuel corresponds to a 4.84 million USD per annum saving in import bills of diesel.

The results also show that, at a national level, total energy cost was 122.267 million USD for diesel tube wells, and 23.067 million USD per year for electric tube wells. For reference, the foreign exchange savings (reduction in diesel inputs) were similar to those found in the study conducted by Mongat, A.S. et al. [34].

3.4. Increase in Farmer's Income

It was observed that most of the farmers were reluctant to share the information regarding their income during interviews. However, 46 out 60 HEIS farmers and 18 out of 24 flood irrigation farmers shared their information. The average profit was then calculated as 1104.07 USD per acre and 2223.09 USD per acre for flood irrigating and HEIS irrigating farms, respectively, as shown in Table 6. This shows a significant increase of a 101% profit earned by HEIS irrigating farms over flood irrigating farms. Moreover, HEIS farmers grow high-value crops, and the others grow conventional crops, resulting in lower incomes.

Table 6. Increase in farmer's income.

Description	Flood Irrigation Farms	HEIS Irrigation Farms
Total per acre profit of farms (USD)	19,873.33	102,262.33
Number of farms	18	46
Average income of farms per acre (USD)	1104.07	2223.09
%age difference	-	101

It was observed that most of the farmers were reluctant to share the information regarding their income during interviews. However, 23 out 40 tunnels farmers and 02 out of 10 non-tunnel farmers shared their information. Moreover, the average profit of farmers growing off-season crops under tunnels was calculated as 2205.71 USD per acre and 950 USD per acre for the crops grown without tunnel cover, as shown in Table 7. This shows an increase of 132% earned by off-season tunnel farmers as their products achieved high prices, resulting in high income. This increase in farmer's income is similar to that found in the studies by Tamoor, M. et al. [26] and Honrao, P. [38].

Table 7. Increase in tunnel farmer's income.

Description	Tunnel Farms	Non-Tunnel Farms
Total per acre profit of farms (USD)	50,731.33	1900
Number of farms	23	02
Average income of farms per acre (USD)	2205.71	950
%age difference	-	132

3.5. Reduction in CO_2 Emissions

The large-scale adoption of solar systems significantly reduces the consumption of fossil fuels, and consequently reduces the environmental impacts associated with fossil fuels. Solar energy technologies provide significant environmental benefits when compared with conventional energy sources, contributing to sustainable development. Consequently, the use of solar PV energy has definite positive environmental implications, especially with the reduction in CO_2 emissions.

The replacement of diesel-powered irrigation with PV-powered irrigation on around 20,000 acres has led to a reduction of 17,622 tons per annum of CO_2 emissions, as 1 L of diesel emits 2.67 kg CO_2. For reference, this reduction in CO_2 emissions is similar to that found in the study conducted by Wazed, S.M. et al. [37].

3.6. Farm Level Job Creation and Industry Development

A growing number of engineers, managerial staff and technicians are being employed by supply and service companies (SSCs), although these supply and service companies usually have to arrange training for their personnel. Thirty-five SSCs were engaged in the installation of PV systems throughout Punjab. The SSCs were pre-qualified through a bidding process, and it was pre-requisite to hire qualified staff including engineers, technicians, and office staff, for proper execution of the projects. Each of the SSCs had to recruit two agricultural engineers, two electrical engineers and five technicians with a diploma in electrical or mechanical engineering. A team of consulting engineers was also engaged for monitoring and the supervision of the projects. The consulting engineers engaged ten agricultural engineers, ten electrical engineers, and office staff. It was mentioned in the PC-1 of the project that the SSCs would train an operator on each project, as solar and HEIS are new technologies for the farmers to adopt. In this way it was estimated that around

2500 jobs were created in addition to the development of the renewable energy industry ensuring environmentally friendly energy for irrigated agriculture.

Many other jobs have been created in agriculture to operate HEIS and PV systems. The interview results have shown that after the installation of HEIS, 50% of agriculture farms hired one person, and 25% of agriculture farms hired two persons to operate the HEIS, respectively, as shown in Figure 4. After installation of the PV system, 71% of agriculture farms hired one person, and 21% of agriculture farms hired two persons for the operation of the PV system, as shown in Figure 5.

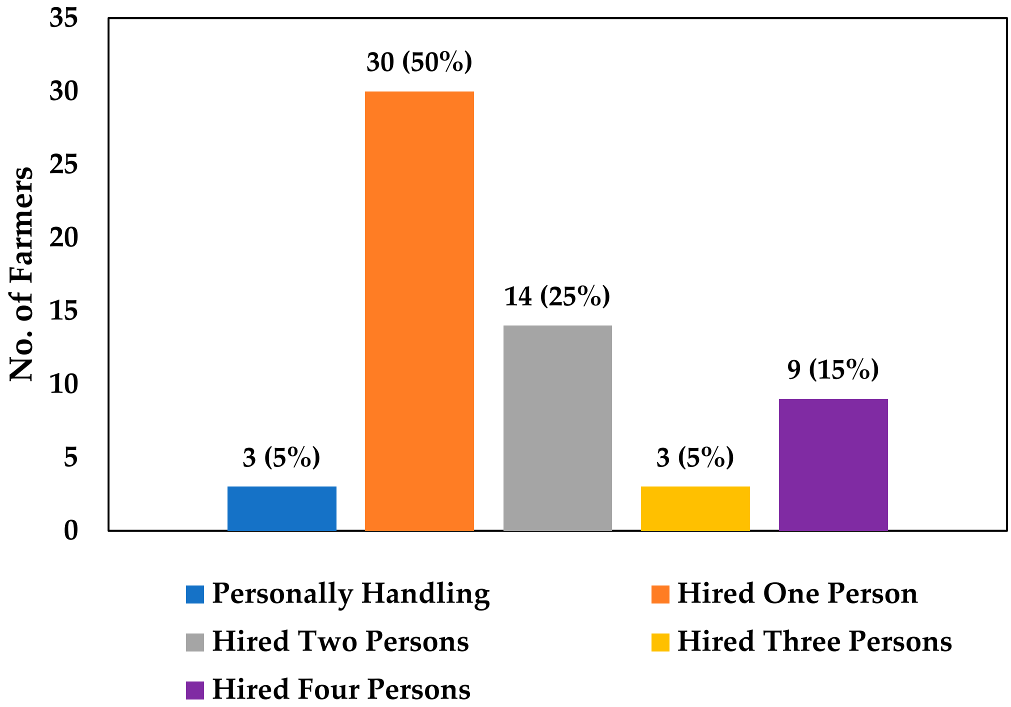

Figure 4. Labor employed after installing HEIS.

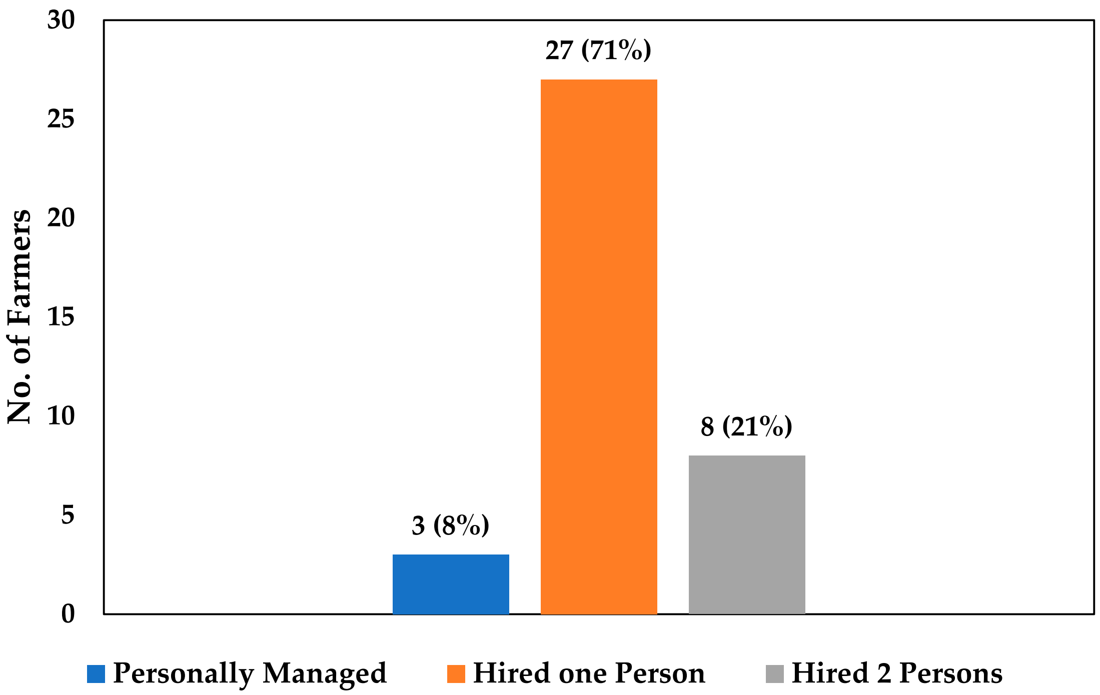

Figure 5. Labor employed after installing PV system.

3.7. Water Savings in HEIS

The analysis of primary data showed the average annual consumption of water was 4863 m^3 per acre in flood irrigation, and 2879 m^3 when irrigating through HEIS. Table 8 shows that HEIS resulted in a 41% water saving. This saving in water is similar to that found in the studies conducted by Tamoor, M. et al. [26] and Honrao, P. [38].

Table 8. Water consumption comparison.

Description	Flood Irrigation Sites	HEIS Irrigation Sites
Water used throughout the year (m^3)	6,141,831	1,618,190
Area irrigated (acres)	1263	562
Water consumption per acre (m^3)	4863	2879
% age difference	-	41%

3.8. Farmer's Satisfaction

The farmers were interviewed during field surveys to understand their satisfaction regarding the operation of HEIS and PV systems. In the questionnaire, farmer's satisfaction level was graded between 1 and 5, corresponding to "not satisfied" and "highly satisfied", respectively. The feedback was then analyzed, and the results are presented in the following sections.

3.8.1. Farmer's Satisfaction on PV Systems Operating HEIS

There were 38 out of 60 HEIS farmers who were operating their HEIS using solar power. The interview results of these 38 farmers have shown that 66% and 31% of them were highly satisfied and satisfied, respectively; they had positive reviews and recommended it to their fellow farmers, as shown in Figure 6. None of these 38 farmers were unsatisfied or less satisfied. All the farmers were either highly satisfied or satisfied that their system was fulfilling crop water requirements, as shown in Figure 7. In addition, 50% of the farmers said that they were achieving very good yields, and 39% said that their yields had been increased and that they were satisfied, as shown in Figure 8. Moreover, 71% of farmers said that they had not incurred any operational costs after PV system installation, as shown in Figure 9. Upon asking the farmers about the 80% subsidy on the PV system, it was noted that as many as 92% of farmers wanted the government to kcontinue providing the same amount of subsidy.

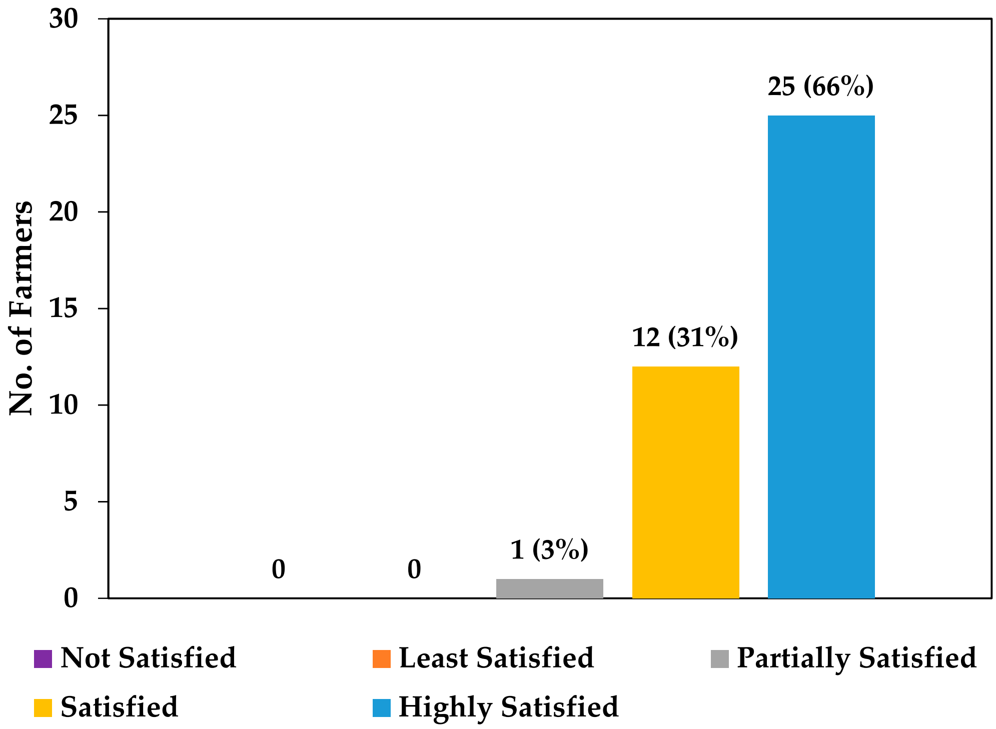

Figure 6. Famers Satisfaction on operations of Solar and HEIS.

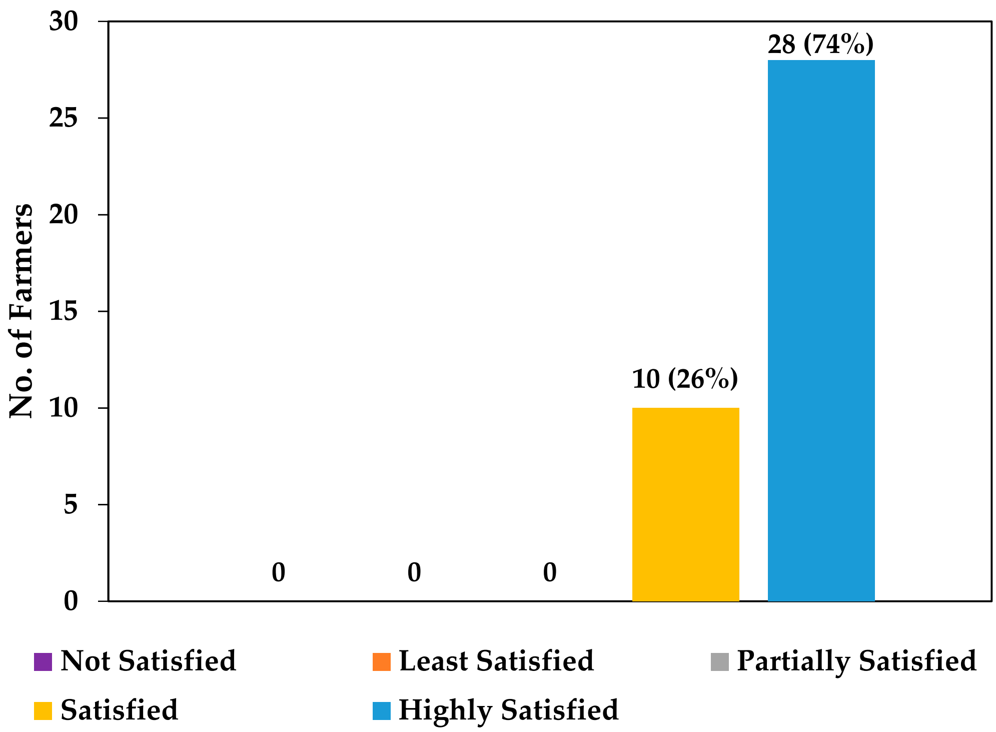

Figure 7. Farmers Satisfaction on Solar and HEIS Fulfilling Crop Water Requirement.

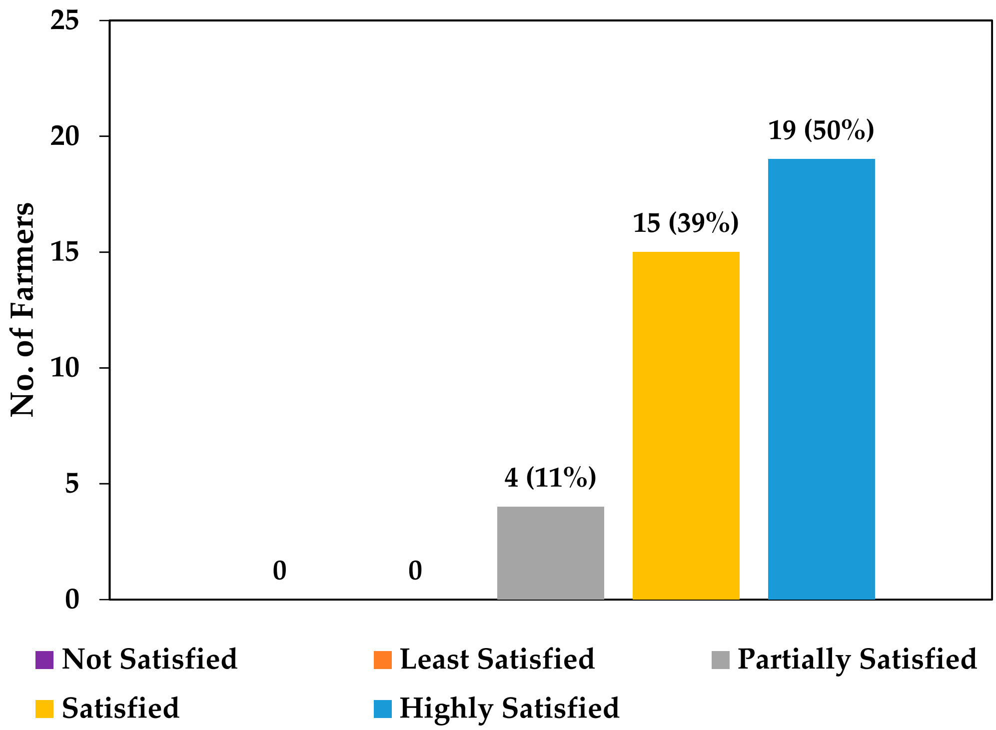

Figure 8. Farmers Satisfaction on yield using Solar and HEIS.

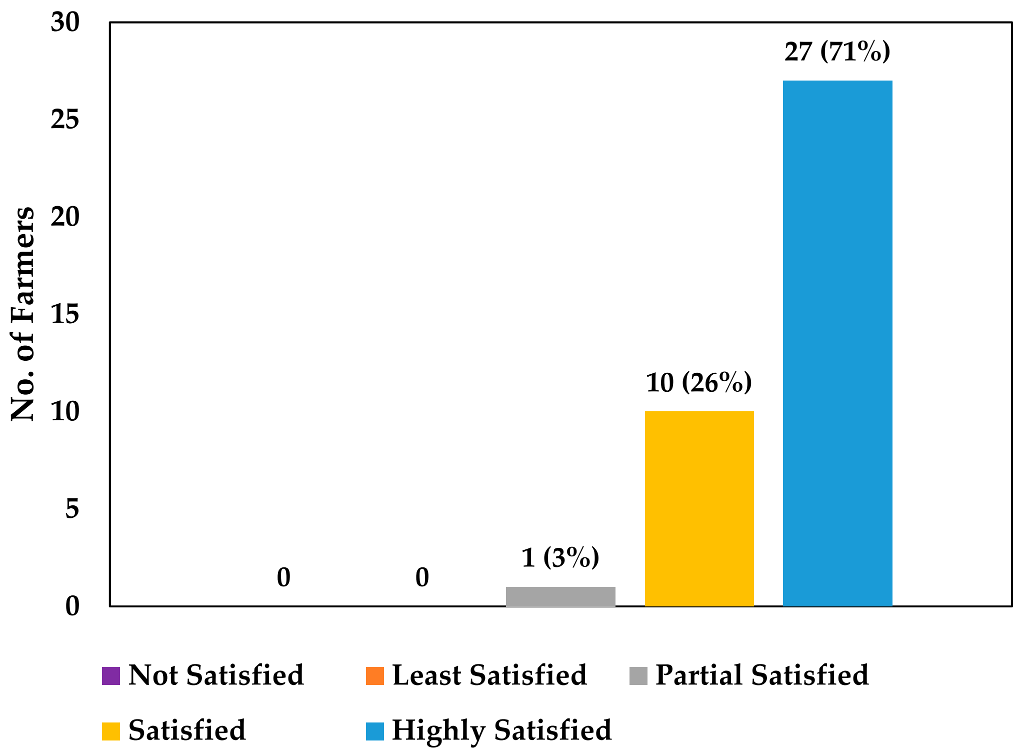

Figure 9. Operating cost of Solar and HEIS.

3.8.2. Farmer's Satisfaction on HEIS

Sixty HEIS farmers, irrespective of their energy source of HEIS, were interviewed. The interview results showed that 51% and 30% of them were highly satisfied and satisfied, respectively, and had positive reviews; however, 4% and 6% were unsatisfied and less satisfied, respectively, as shown in Figure 10. The percentage of farmers who were highly satisfied or satisfied with the HEIS system operation was 57% and 23%, respectively, as shown in Figure 11. In addition, 60% and 32% farmers were highly satisfied or satisfied that their system was fulfilling crop water requirements, as shown in Figure 12. Moreover, 54% of the farmers said that they were achieving very good yields and 28% said that their yields had increased from previous years, and they were satisfied, as shown in Figure 13. Upon asking the farmers about the 60% subsidy on the HEIS, it was noted that more than half of farmers wanted the government to increase the amount of subsidy.

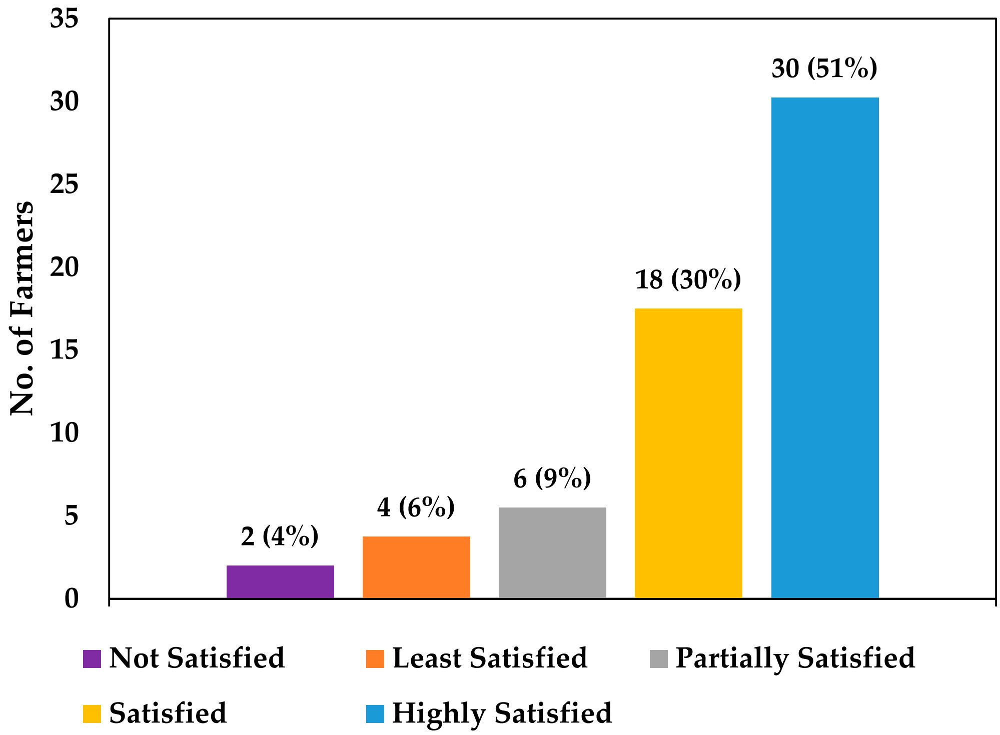

Figure 10. Farmers' Overall Satisfaction with the HEIS.

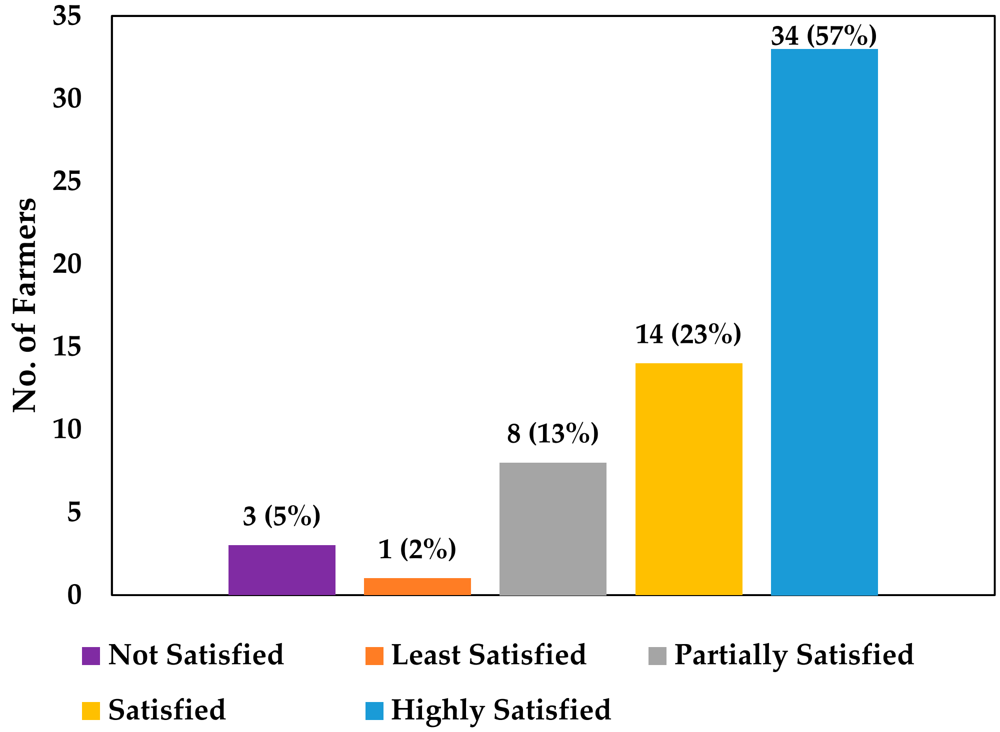

Figure 11. Farmers' Satisfaction on Operations of HEIS.

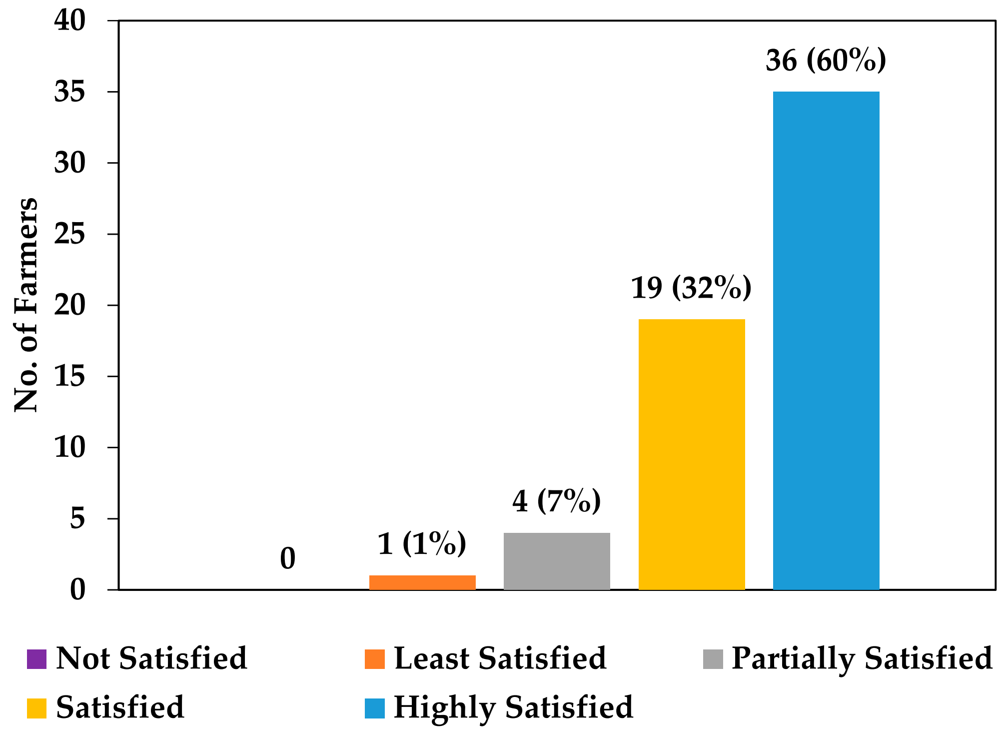

Figure 12. Farmers' Satisfaction on HEIS fulfilling crop water requirements.

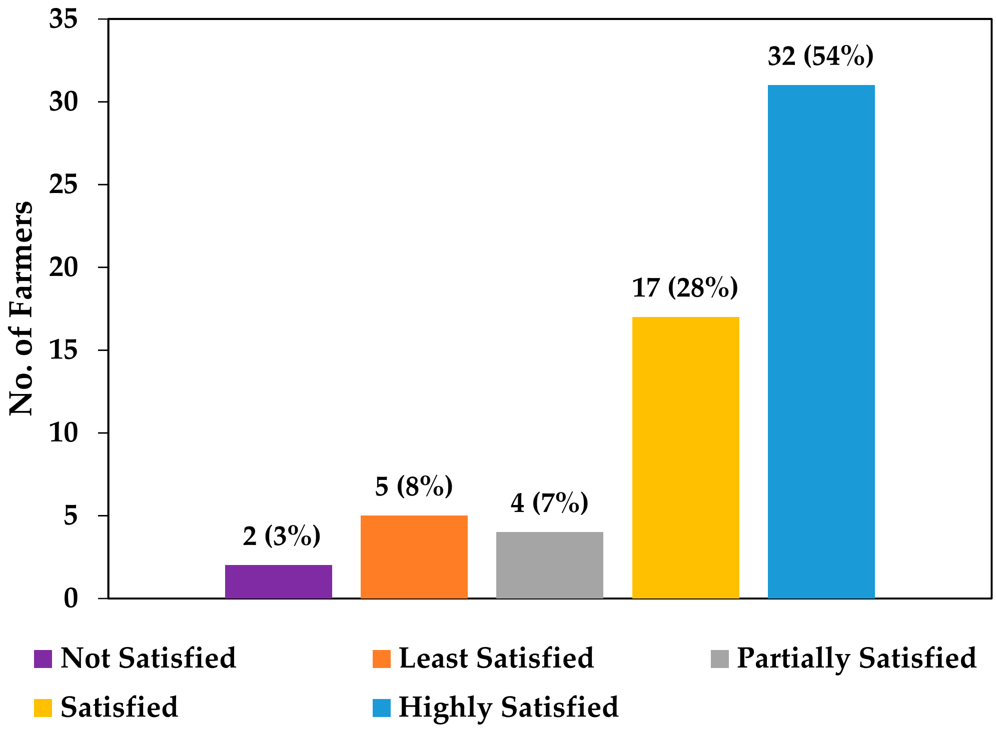

Figure 13. Farmers' Satisfaction on yields with HEIS.

3.8.3. Farmers' Satisfaction Regarding Tunnel Farming

There were 40 out of 84 farmers who were growing off-season vegetables under tunnels. Of the farmers, 95% had installed walk-in tunnels, and only 5% had low or high tunnels. Upon asking the farmers about achieving good yields from tunnels, 50% and 35% of the farmers said that they were highly satisfied and satisfied, respectively, and 15% farmers said that they were very less satisfied with the cost of production in tunnel farming, as shown in Figure 14. However, Figure 15 depicts that 43% and 38% of farmers said that they were highly satisfied and satisfied on tunnel farming cost, respectively. Furthermore, 50% of farmers were highly satisfied on tunnel farming operations, as shown in Figure 16.

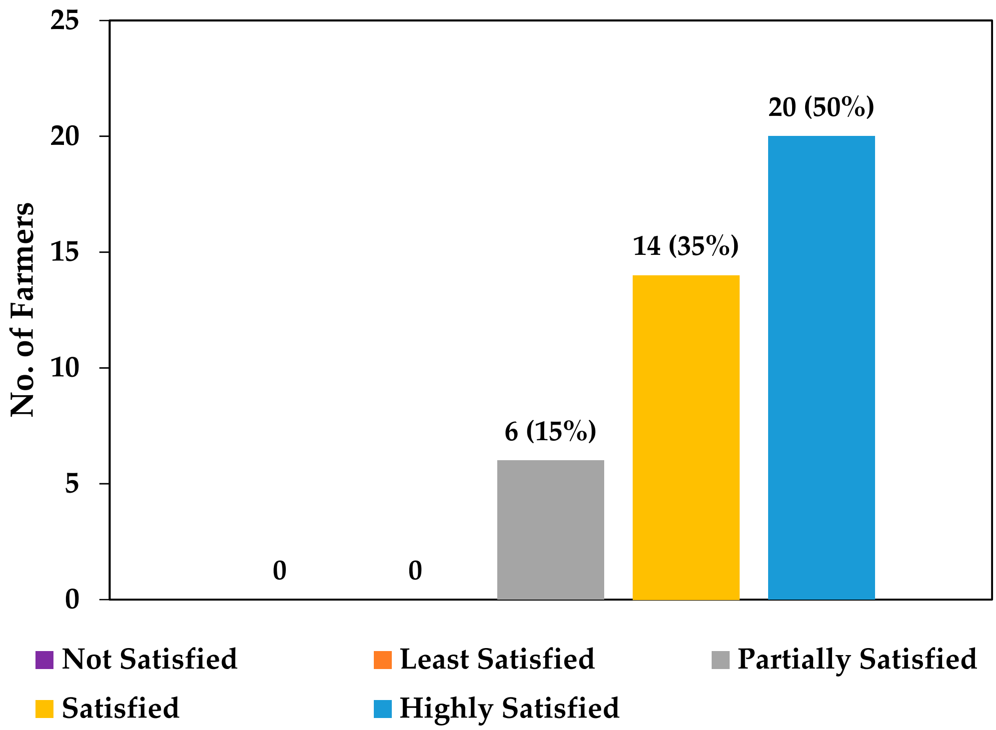

Figure 14. Farmers' Satisfaction on yields in Tunnels.

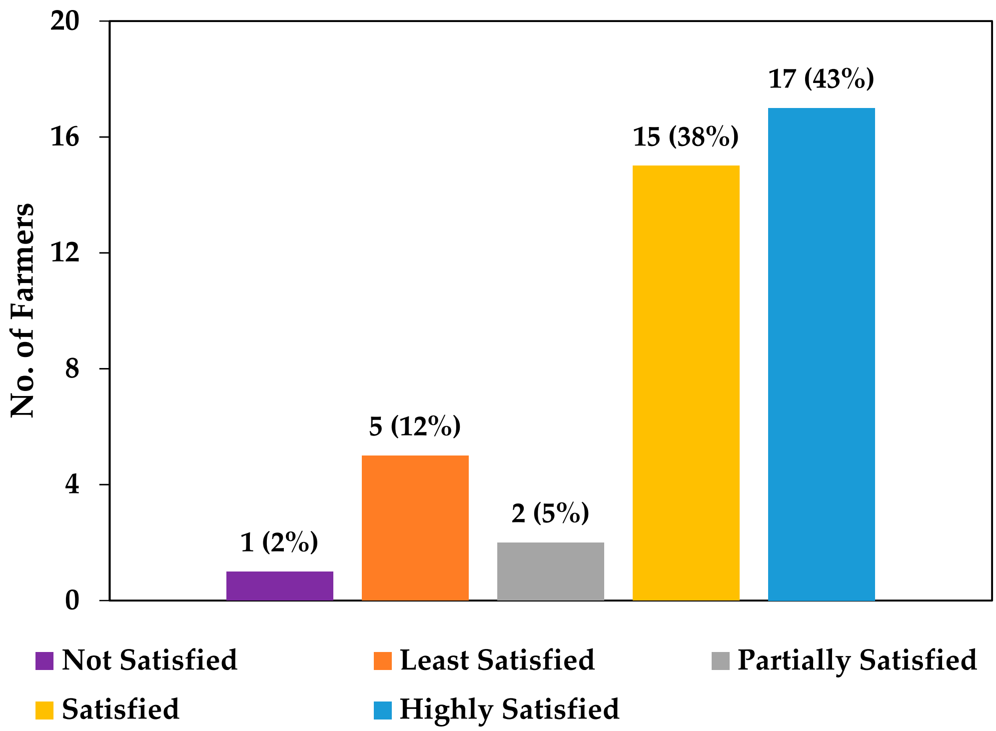

Figure 15. Farmers' Satisfaction on Tunnel Farming Cost.

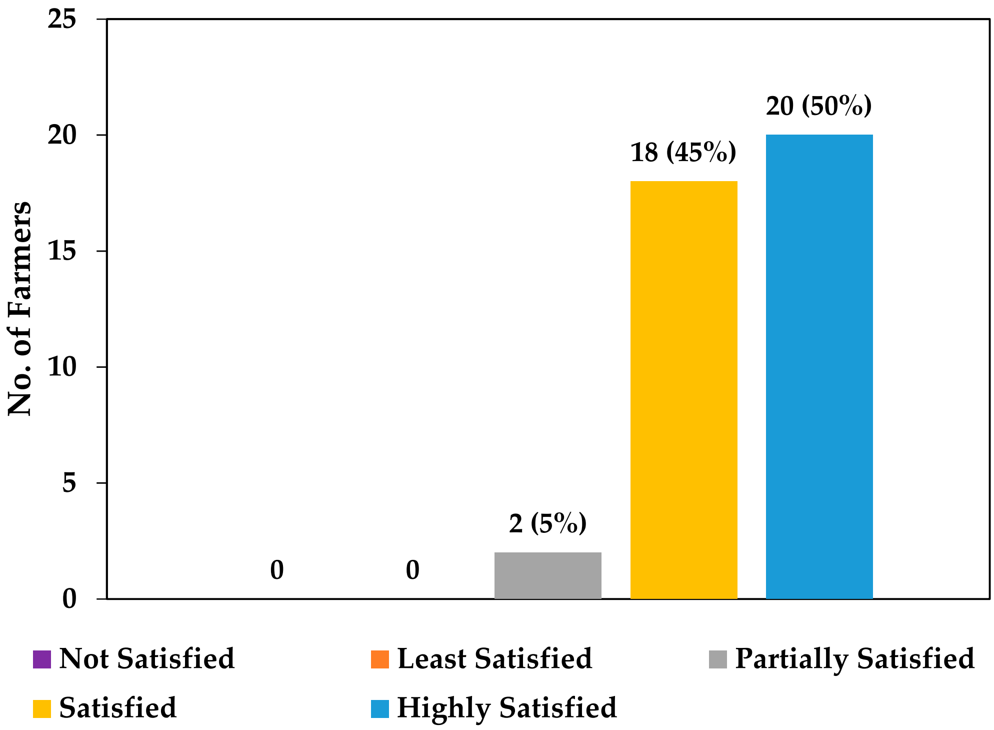

Figure 16. Farmers' Satisfaction on Tunnel Farming Operations.

3.9. Economic Viability of PV Power Irrigation

Although the cost of PV system has decreased significantly, the economic viability of PV-operated high-efficiency irrigation systems fluctuate. The payback period varies from site to site, depending on site conditions, crop type and markets, energy resources (such as electricity from grid, diesel, etc.) and prices of fuels which may be subsidized. The pay-back period for the complete photovoltaic-operated HEIS cost is significantly shorter compared with other countries of the region because of the non-subsidized higher price of both electricity and diesel in Pakistan, as well as the larger size of land owned by farmers. For reference, the economic viability of PV-power irrigation is similar to that found in the studies conducted by Tamoor, M. et al. [26] and Mindú, A.J. et al. [7].

4. Challenges and Recommendations

4.1. Challenges

- Direct pumping of groundwater in order to feed the drip irrigation system is one of the most effective, resourceful and economical alternatives. This ingenious intervention is no doubt economizing the operational costs of HEIS, is climate smart, and reduces the on-grid load of electricity to pump the groundwater for pressurized irrigation. However, it is observed that these PV systems are being used for groundwater pumping that is subsequently used for flood irrigation to the same crop or other crops grown at the farm. This situation is highly unfavorable in all aspects. It is strongly recommended that suitable measures should be taken to conserve groundwater aquifers against depletion because of indiscriminate groundwater pumping;
- The high upfront cost of PV compared with conventional pumps limits its adoption. The upfront cost of a PV system per HP is six times the monthly income of average farmers, and eight times the cost of a diesel or electric pump with similar power;
- Limited capacity of technicians and labor to handle the equipment is also a challenge.

4.2. Recommendations

- Considering the overall energy and water situation in the country and cost comparison given above, it is suggested that the use of solar PV energy may be encouraged for operating high-efficiency irrigation systems;
- Monitoring and controlling the PV systems remotely is suggested to avoid indiscriminate groundwater pumping;
- Power evacuation through net metering may be considered from the PV systems installed in on-grid areas;
- Service and supply companies need to improve after sale services to the farmers;
- The amount of subsidy should be reduced to 50% and farmers should be supported to obtain a loan to finance their share;
- Maximum size of the PV system should be fixed for each district to ensure that there is no extra energy available for flood irrigation using groundwater. In this regard, the total dynamic head (TDH) of a drip system should be estimated based on the depth of the ground water table for different geographical locations, as declared by the concerned authorities.

5. Conclusions

Analysis has proven that photovoltaic systems operating high-efficiency irrigation systems (HEIS) can provide clean, climate-smart, and innovative energy technologies for efficient irrigation systems in remote areas (especially areas that are not connected to the national utility grid or conventional power sources); this can bring huge socio-economic and environmental benefits. In countries with water shortages, especially in desert areas, PV-powered HEIS helps to stabilize and increase crop production and reduce the impact of drought, in order to overcome the pressure of water shortages in the dry season. PV-powered HEIS will encourage farmers to grow high-value crops such as orchards and vegetables, which will help to reduce poverty in remote areas.

PV systems with a capacity of 17.29 MWp were installed to operate HEIS at around 20,000 acres under this subsidy project, resulting in an annual saving of 6.6 million liters of diesel. This saving in fuel corresponds to a saving of USD 4.84 million per annum in import bills of diesel. A cost comparison of 7.46 kW pumping systems powered by solar, diesel and electricity was performed. The unit cost of PV-powered HEIS was found as 0.1219 USD/kWh which was 4% and 66% less than the subsidized electricity cost and diesel cost, respectively.

The study has shown that the farmers using PV-powered HEIS were highly satisfied, had positive reviews, and recommended the technology to their fellow farmers. None of the farmers was unsatisfied or less satisfied. All the farmers were either highly satisfied or satisfied that their system was fulfilling crop water requirements. Moreover, 50% of the farmers said that they were achieving very good yields, and 39% said that their yields had been increased from previous years, and they were satisfied. In addition, 71% of farmers said that they had not incurred any operational costs after PV system installation. Upon asking the farmers about 80% subsidy of the PV system, it was noted that as many as 92% of farmers said that the government should continue providing the same amount of subsidy.

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Abbreviations

The following abbreviations are used in this research paper:

HP	Horse Power
AC	Alternating current (A)
CO_2	carbon dioxide (CO_2)
DC	Direct current (A)
GHI	Global horizontal irradiance
kWh	Kilowatt hour
MWh	Megawatt hour
Nos	Numbers
HEIS	High-Efficiency Irrigation Systems
PV	Photovoltaic

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