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Review

Solar Irrigation Potential, Key Issues and Challenges in Pakistan

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Abstract: Pakistan faces water scarcity and high operational costs for traditional irrigation systems, hindering agricultural productivity. Solar-powered irrigation systems (SPIS) can potentially provide a sustainable and affordable solution, but face technical, financial and policy barriers to adoption. A comprehensive study is needed to examine feasibility and identify barriers. Therefore, a comprehensive review study is conducted to identify the potential for solar irrigation, key issues and challenges related to its implementation in Pakistan. The analysis is based on published studies, technical reports and a survey of solar-powered drip irrigation systems. The use of SPIS in Pakistan is becoming a cost-effective and sustainable option for irrigation, particularly in remote and off-grid areas. However, these systems also have their challenges, such as high initial costs, maintenance and repairs, limited access to spare parts, lack of government policies and regulations, lack of technical expertise, lack of financing options and social acceptance. The most pressing issue is the risk of groundwater exploitation by using SPIS. Based on the analysis of the energy and water situation in Pakistan, it is important to sustainably use both solar energy and groundwater resources, through the implementation of effective management strategies and policies. With the right policies and investment in research and development of SPIS and groundwater, farmers can benefit by increasing crop yields, conserving water resources, reducing the cost of energy, increasing productivity and improving the standard of living and access to electricity in remote and off-grid areas. It is recommended that the adoption of solar energy be promoted to run high efficiency irrigation systems (HEIS) with urgent capacity improvement among farmers, advisors and system installers to sustainably manage water resources in SPIS. This would not only help to reduce the consumption of fossil fuels and associated environmental impacts, but also increase farmers' income and reduce their operational costs. Moreover, the use of SPIS can improve crop yields, leading to food security and poverty reduction. Thus, the government and policymakers should consider implementing policies and incentives to encourage the large-scale adoption of solar energy in the agricultural sector.

Keywords: solar energy; solar irrigation; HEIS; groundwater extraction; tube wells; Pakistan

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1. Introduction

The world's largest employer is agriculture, which plays a critical role in global food security [1]. Irrigated agriculture is a key measure to improve agricultural productivity, reduce climate change vulnerability, ensure food security and generate income for farmers [2]. Energy is a key input for powering high efficiency irrigation systems and tube well irrigation, which can be expensive and often relies on fossil fuels, contributing to greenhouse gas emissions and exacerbating climate change [3]. To address these challenges, there is a need to develop and promote more sustainable energy sources for irrigation, such as solar power to improve the efficiency of existing systems through better maintenance and management. Therefore, this study is conducted to access the solar energy and solar irrigation potential in Pakistan. According to Shah and Akbar [4], Pakistan has no specific national policy on solar technology for groundwater pumping and there is the risk of groundwater over exploitation by using solar tube wells/pumps. Pakistan is the third largest user of groundwater for irrigated agriculture in the world, and it is estimated that about 73% of its area is directly or indirectly irrigated using groundwater extraction of 60 billion m^3 [5]. According to one estimate, there are around 1.2 million tube wells and nearly 16% use electricity, whereas the remaining are diesel operated [6]. Out of 1.2 million tube wells, 85% are in Punjab while the other 15% are in Sindh (6.4%), Khyber-Pakhtunkhwa (3.8%) and Baluchistan (4.8%). Farmers prefer diesel tube wells due to low installation and operational costs compared to electric tube wells. The shallow depth and better quality of groundwater has favored the huge development in private tube wells in Punjab [7].

In Pakistan, the pumping cost of 1000 m^3 of water from a deep tube well is three times higher than a shallow tube well [8]. Recently, the increasing cost of energy (both diesel and electricity) is becoming a serious issue for small landholder farmers, while on the other hand, there is a frequent shutdown of electricity that may enhance the risk factor of crop water requirement at the time of crop demand [9]. In this situation, a solar-powered irrigation system is a viable option in the present energy situation. Solar energy is an environmentally friendly, cheap source of green energy that is available for 300 days a year with 8 h of effective daylight [10]. The coupling of an irrigation system with solar energy is called a solar-powered irrigation system (SPIS). This consists of either direct pumping, such as a tube well, or is equipped with high efficiency irrigation system, such as a drip or sprinkler. Solar water pumping systems involve no fuel cost [11], preserve grid electricity, eliminate the use of high-priced diesel, promote irrigated agriculture in remote areas and improve the socio-economic development of farmers in remote areas [12,13]. Coupling drip irrigation systems with solar energy promotes irrigated agriculture in remote areas, as well as in arid and semi-arid areas [14]. According to Akram and Asif [14], solar-powered drip irrigation systems offer a favorable return on investment compared to electric- and diesel-powered drip irrigation systems.

In this regard, water and energy are two vital resources for efficient agricultural production to utilize energy (here, solar) to pump water to fulfil crop water requirements. However, for small landholders in remote arid and semi-arid areas, both resources are hard to obtain when required. They may not have as much water as is needed or the energy to pump it. Therefore, the farmers can link high efficiency irrigation systems (HEIS), such as drips or sprinklers, with solar energy systems to achieve more crop per drop and high water-use efficiency, energy efficiency and cost efficiency [15]. Solar energy systems can be directly used for pumping water with tube wells for irrigation purposes. Solar irrigation systems (here, HEIS) are a more efficient system because farmers can obtain more crop production per unit of water with no recurring fuel costs. Solar energy can be harnessed through photovoltaic (PV) panels to pump water, ideally in remote locations. It has been estimated that there are about 3000 sunny hours per year with 5 to 7 kWh/m^2 of solar irradiation that can be fully utilized in solar-powered irrigation systems [16,17]. Pakistan has high solar irradiation, with a total installed power of 1083 MW, but there has been slow progress in adopting this technology [18]. The agricultural sector has benefitted from this technology for irrigating lands using solar-powered drip and sprinkler systems under a subsidy scheme launched by the government of Punjab, Pakistan, in 2016–2017 (the details are discussed in Section 5). Therefore, the specific objective of this review study is to realize the potential of solar irrigation, the key issues and challenges in Pakistan and to develop a clear understanding of the opportunities and constraints associated with SPIS. The analysis of this review study in Pakistan is presented in eight sections. After the introduction (Section 1), solar energy potential and solar irrigation are analyzed in Sections 2 and 3. In Section 4, policies related to solar technology in agriculture are outlined at the provincial and federal levels. In Section 5, a case study undertaken throughout the Punjab, Pakistan, on solar-powered HEIS is analyzed to evaluate its socio-economic impact and adoptability. In Section 6, SPIS planning, design and suitability criteria are highlighted for farmers, service providers and researchers interested in this technology. In Section 7, the benefits, risks, challenges and opportunities presented by SPIS are discussed. The review ends with a conclusion and recommendations in Section 8.

2. Solar Energy Potential in Pakistan

The Pakistan boundary covers an area of 796,096 km^2 with latitudes 23°35′ to 37°05′ N and longitudes 60°50′ to 77°50′ E. The areal belt is sunny with a high level of insolation (95% coverage), adequate sunshine hours (8 to 8.5 h a day) and 185 to 290 sunny days in a year [19,20]. The horizontal surface of the boundary receives a mean global irradiance of 200 to 250 W/d, resulting in 1500 to 3000 sunshine hours per year depending on different locations [21]. According to an estimate, this amount provides sufficient electricity to more than 40,000 villages [20]. Pakistan has potential for 2.9 million MW of solar energy [22].

Global horizontal irradiance is a good resource measurement for solar photovoltaic (PV) installations. The Renewable Energy Resource Mapping program is the initiative of the World Bank and is financed by the Energy Sector Management Assistance Program (ESMAP), providing information on solar resources and the PV power potential of Pakistan with the help of Solargis [23]. The detailed data indicated that Pakistan has a PV power potential of 1200 kWh/kWp to 2100 kWh/kWp per year harnessed from the yearly sum of global horizontal irradiation (1300 to 2300 kWh/m^2) throughout Pakistan, as shown in Figures 1 and 2. Pakistan has better solar irradiation in the southern and southwestern parts than the north, and the solar potential (especially in the Sindh and Baluchistan provinces) is the second highest in the world [24].

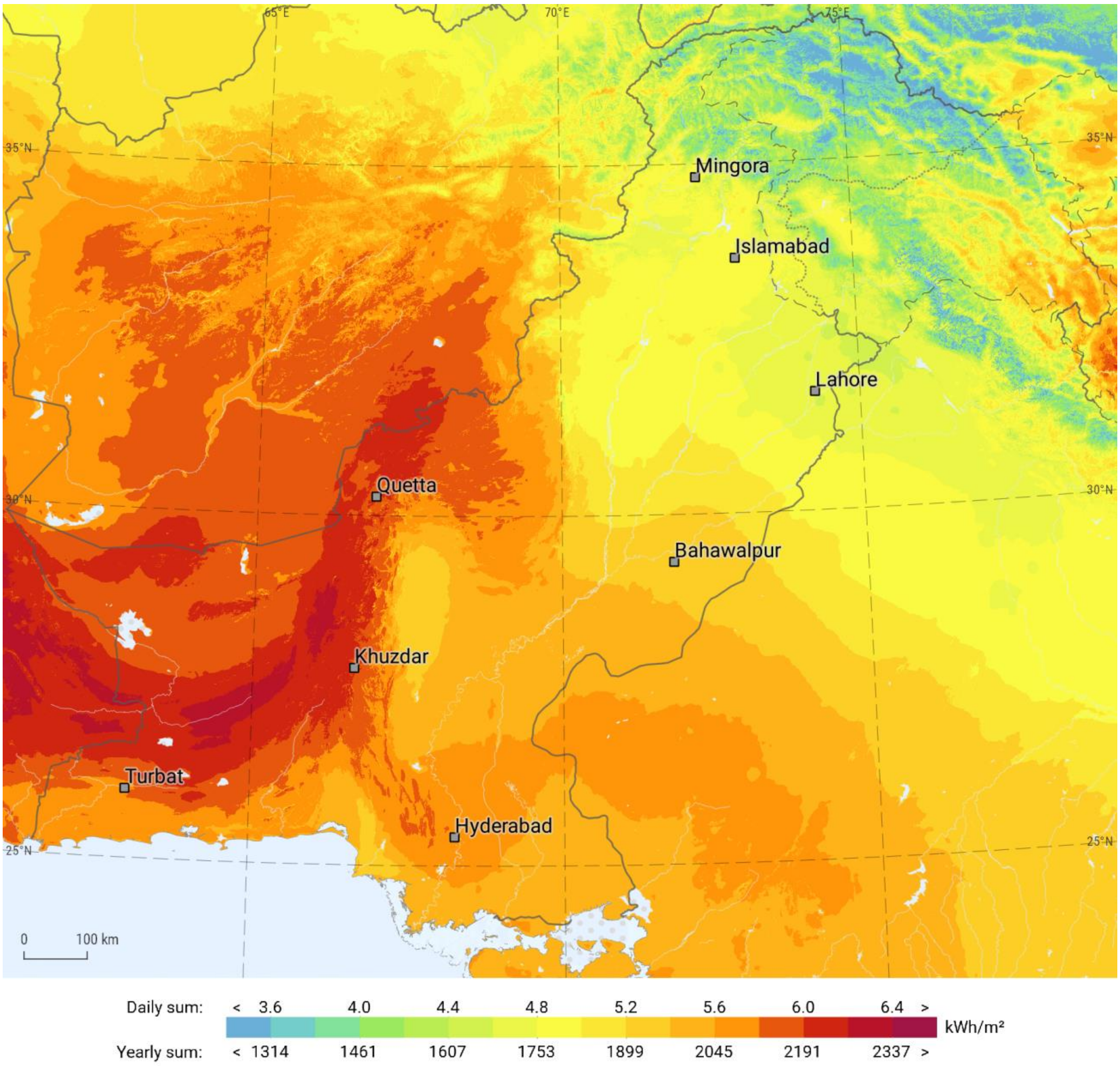

Figure 1. The daily and yearly sum of global horizontal irradiation (kWh/m^2) of Pakistan [25].

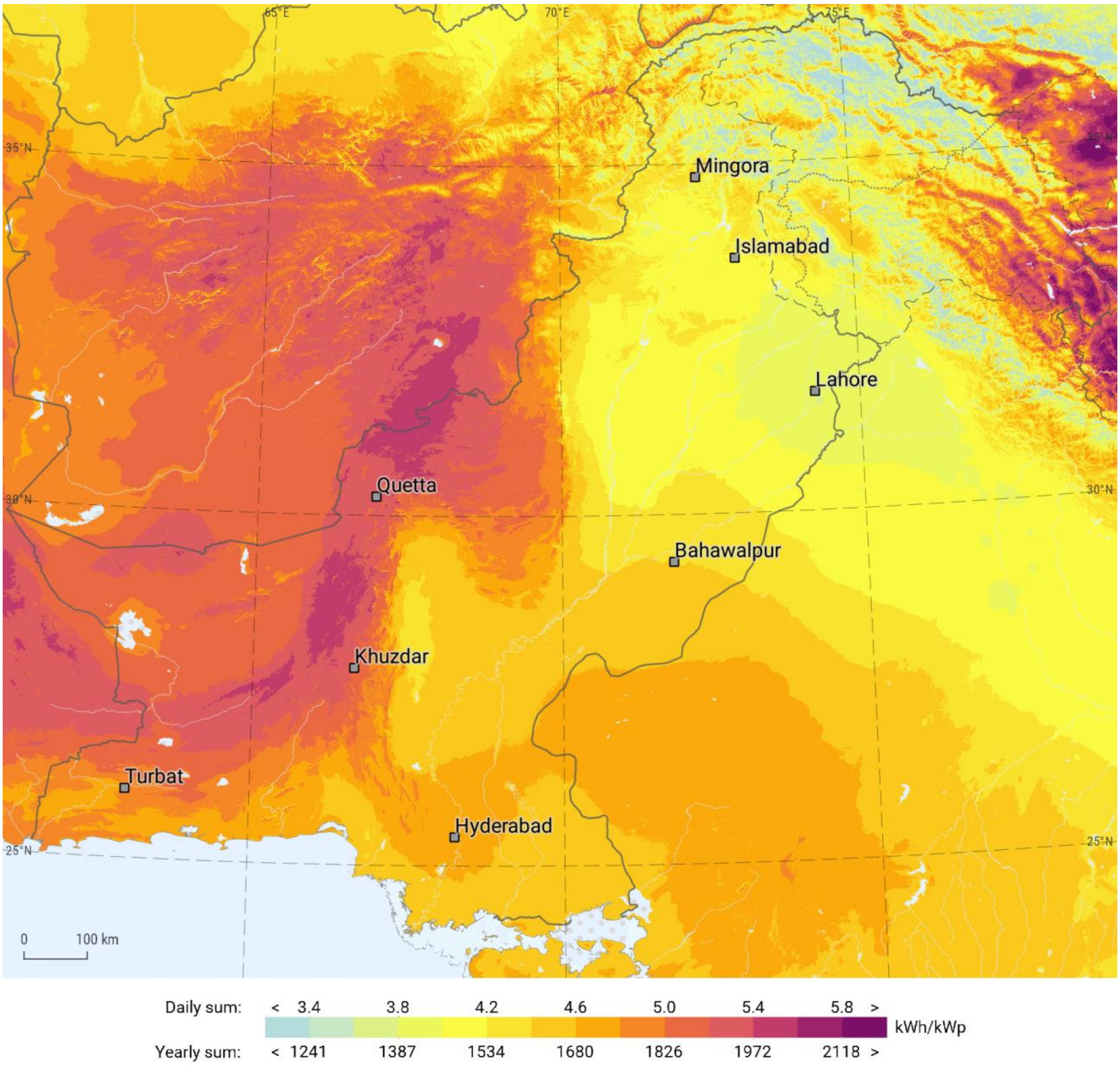

Figure 2. The photovoltaic power potential of Pakistan for an open-space fixed-mounted PV system [25].

Pakistan has significant potential for solar energy due to its high solar radiation and large land area. According to the National Renewable Energy Laboratory (NREL), Pakistan has a solar energy potential of approximately 5500 TWh/year, which is equivalent to more than five times the country's current electricity consumption. A study [26] found that Pakistan's solar energy potential is particularly high in the southern and western regions of the country, where solar radiation levels are among the highest in the world. The study estimates that these regions have the potential to generate more than 20,000 GW of electricity from solar energy. Another study [27] found that Pakistan has high potential for solar energy in both on-grid and off-grid applications. The study estimates that the country has the potential to generate more than 10,000 GW of electricity from solar energy, which is equivalent to more than 50% of Pakistan's current electricity consumption. The study also found that solar energy can provide a reliable source of electricity for remote and off-grid areas, which can help to improve access to electricity in these areas. However, to fully realize the potential of solar energy in Pakistan, several challenges need to be addressed.

According to the World Bank, Pakistan's current electricity demand can be fulfilled by utilizing only 0.071% of its area for solar photovoltaic energy [28] because the average annual solar insolation potential is 5.30 kWh/m^2, which can produce 175,800 GW of solar energy [29]. The solar market in Pakistan is still at an early stage, but there is significant potential for fulfilling the country's energy requirements through solar resources [30]. Many efforts have been made to set up and increase solar energy penetration in agriculture, as well as domestic and industrial uses in Pakistan [20]. Under a development program initiated by the International Renewable Energy Agency in collaboration with China and private-sector energy companies in Pakistan, solar power plants are currently being developed in Punjab, Sindh, Balochistan and Kashmir. In addition, the Quaid-e-Azam Solar Park, which is Pakistan's first photovoltaic power station with a capacity of 1000 MW, has been completed in Bahawalpur.

3. Solar Irrigation in Pakistan

Pakistan has a total surface water potential of 145 million acre-feet (MAF) and a groundwater potential of 60 MAF, from both, 97% is used for agriculture, where 60% of this is directly or indirectly fulfilled by groundwater [31]. Approximately, there are 1.3 million tube wells (the distribution of tube wells in provinces and growth rates are shown in Figures 3 and 4) of which 83% are diesel-powered operated while the growth of electricity tube wells has slowed down due to a rise in the electricity tariff and power outages. Solar pumping technology has emerged as a viable alternative to traditional diesel and electric pumps in recent times. All provincial governments have either planned or implemented subsidized solar irrigation pump schemes, often coupled with High-Efficiency Irrigation Systems (HEIS). While solar irrigation pumps (SIPs) hold great promise in replacing diesel pumps, there are several reasons for the slow adoption rate of this technology. For instance, farmers are not yet willing to shift from flood irrigation to HEIS techniques, and the initial costs of SIPs are high. Additionally, SIPs have lower discharge capacities compared to diesel-powered pumps, and the costs of solar-powered pumping systems significantly rise with an increase in pumping depth and discharge. The government of Punjab, Pakistan, is providing an 80% subsidy on the installation of a HEIS coupled with a solar system. The government of Khyber Pakhtunkhwa has also initiated a 50% subsidy scheme on SIPs in rainfed and water-scarce areas. The Sindh government has launched several solar-powered tube well schemes to strengthen the agriculture sector. In 2017, the federal government and Baluchistan agreed to replace 30,000 grid-connected tube wells with SIPs, but to date, this project has not materialized.

Pakistan is an agricultural country facing several challenges such as water scarcity and a lack of efficient irrigation systems. Solar irrigation has the potential to address these challenges and improve agricultural productivity in Pakistan. According to an estimate, solar irrigation can provide irrigation water to about 1.5 million hectares of land in Pakistan [4]. Solar energy is abundant, with an average annual solar radiation of 5.5 to 6.5 kWh/m^2/day, indicating the significant potential of solar irrigation to improve agricultural productivity and water management in Pakistan as it can provide a reliable and sustainable source of irrigation water for farmers, particularly in remote and off-grid areas [32]. Solar irrigation systems were first introduced in Pakistan in the 1980s. However, their widespread adoption and use in the country did not occur until the 2000s. The Pakistan Council of Renewable Energy Technologies (PCRET), established in 1995, has played a key role in the development and promotion of solar irrigation systems in the country. PCRET's efforts to promote the use of solar energy for irrigation have included the development of low-cost solar irrigation systems, the training of farmers and technicians as well as the conduct of research and development on solar irrigation technology.

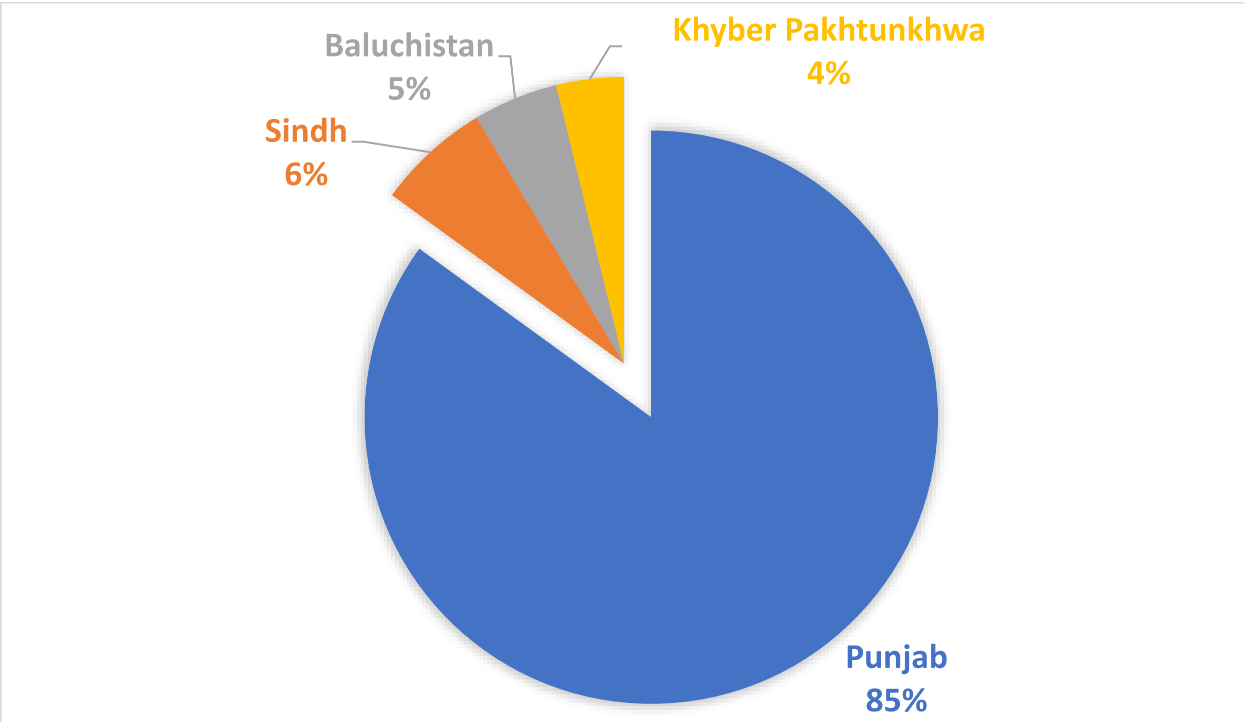

Figure 3. The percentage share of tube wells, by provinces of Pakistan.

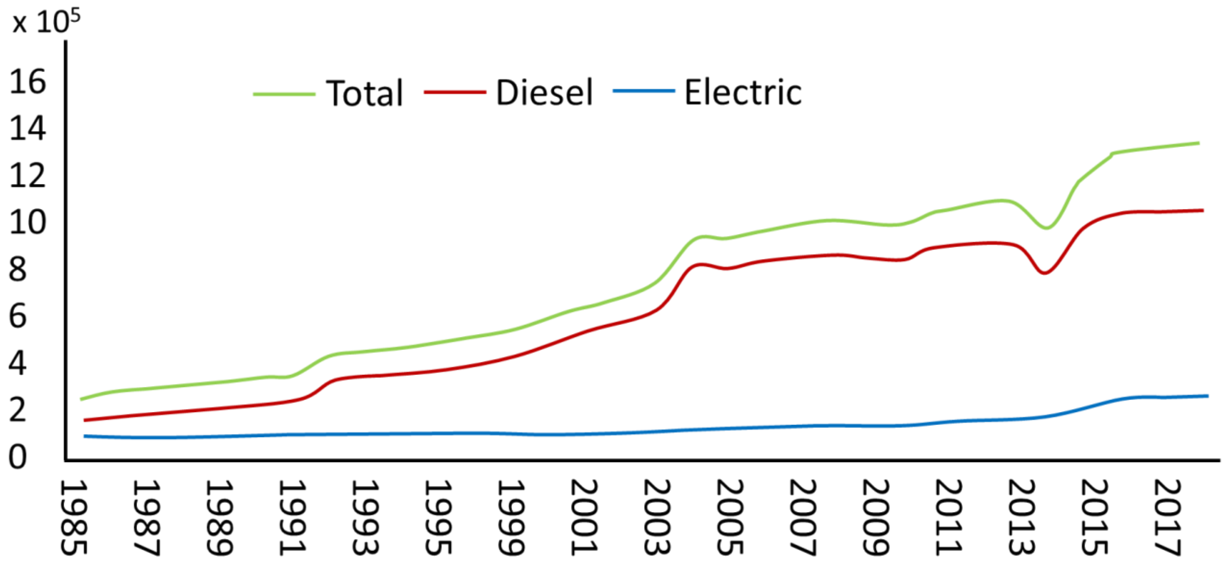

Figure 4. Growth of tube wells in Pakistan.

Solar irrigation systems can be divided into two main categories: small-scale and large-scale systems. Small-scale systems are designed to meet the irrigation needs of small landholdings and are typically used for horticultural crops and orchards. These systems consist of a small solar panel, a water pump, and a water storage tank. Large-scale systems are designed to meet the irrigation needs of larger landholdings and are typically used for field crops. These systems consist of a larger solar panel, a water pump and a water storage tank. In recent years, the government of Pakistan has also recognized the potential of solar irrigation and has taken steps to promote its use in the country. For example, the government has launched several initiatives to provide subsidies and financial assistance to farmers to purchase and install solar irrigation systems. Additionally, several non-governmental organizations and international development agencies have also been working to promote the use of solar irrigation in Pakistan.

Pakistan lacks a specific policy on SIPs, while various policies are relevant to solar technology for groundwater pumping in agriculture. Water professionals are apprehensive, in that a shift to PV solar pumping may result in uncontrolled pumping and exacerbate groundwater depletion. The number of solar irrigation systems in Pakistan has been growing in recent years, however, the adoption of solar irrigation in the country is still not widespread. The government of Pakistan and other organizations have been working to promote the use of solar irrigation in the country, but more efforts are needed to fully realize the potential of this technology in addressing the water scarcity and irrigation challenges faced by farmers in Pakistan. It is worth mentioning that, as per our knowledge cut-off, there are no specific data available on the exact number of solar irrigation systems installed in Pakistan since 2000. However, it is known that the adoption of solar irrigation in the country has been slow and more efforts are needed to increase the number of systems installed. Factors such as a lack of awareness and knowledge, a lack of access to finance and a lack of technical expertise are some of the barriers that have slowed down the adoption of solar irrigation in Pakistan.

The government of Pakistan is considering an alternate option to switch 1.3 million agriculture tube wells to solar energy to reduce input costs and enhance farm income, particularly that of the small landholders. Under the "free solar pump scheme" the government of Pakistan will provide a free solar pump to low-income families and poor farmers. This, statistically analyzed as the total cultivated area of Pakistan, is 42.6 million acres (MA), of which 13.89 MA is conjunctively irrigated using canal and tube well water. The area irrigated by tube wells is only 6.08 MA, while the estimated coverage is 12 MA. With a rate of 0.5 kW per acre, the solar PV potential is 6000 mega watt (MW). The average horsepower (hp) required per tube well is 17 hp (12.68 kW), while the optimal number of days of operation of solar PV is 300 days per year. For diesel and electric, the number of days of operation is 125 and 184 days per year, respectively. Therefore, the estimated solar PV demand for 300 days of operations is equal to 8400 MW. Assuming a target of 50% conversion in 10 years, the estimated solar PV demand is 4200 MW, while on a yearly basis it is 420 MW (with 110,000+ solar pumps). Converting 50% diesel- and electric-operated pumps to solar can reduce the 4200 MW electricity load that can be put to productive use and reduce the consumption of diesel and fuel import bills. On the other hand, replacing diesel tube wells with SIPs can significantly reduce CO_2 emissions. According to an estimate, diesel tube wells contribute approximately 5.025 million metric tons of CO_2 emissions per year [33]. A greater emphasis on solar power can reduce the cost of electricity generation, lower greenhouse gas emissions and help to address the cost-tariff deficit without the need for tariff hikes that would adversely affect end-users and businesses [9]. According to NEPRA's announcement in January 2019, the average cost of electricity generated from solar PV is approximately 70 USD/MWh [9]. Despite being cheaper than thermal and hydropower plants, solar power only contributes 1% to Pakistan's power generation mix, as depicted in Figure 5. However, solar photovoltaics (PV) are expected to become even more cost-effective in the future, with costs anticipated to significantly decrease [34].

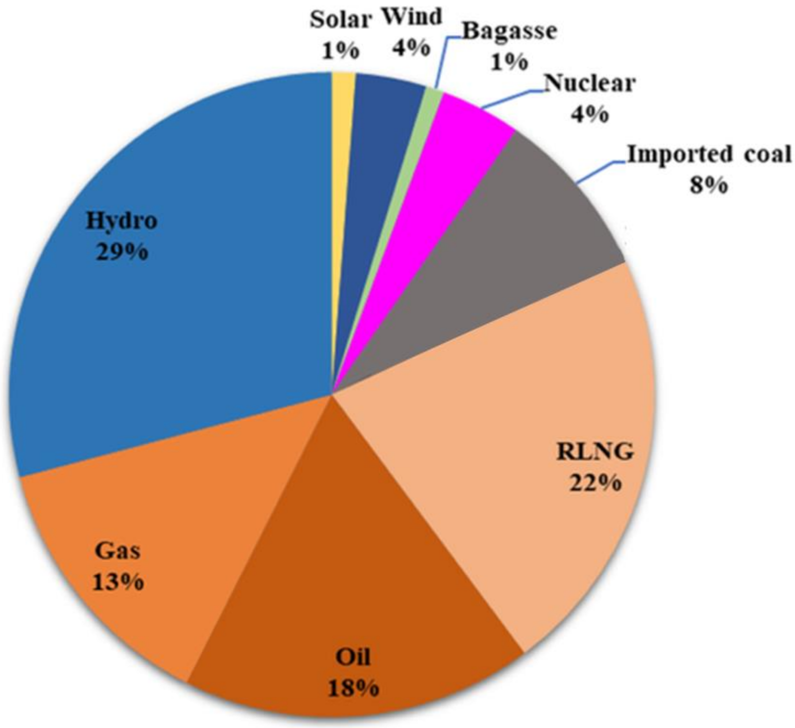

Figure 5. Power generation mix of Pakistan in the year 2018 [34]; RLNG—Re-gasified liquefied natural gas.

4. Policies Related to the Use of Solar Technology in Agriculture

Although there is no specific national policy on solar technology for groundwater pumping in agriculture. A study [27] found that a lack of government policies and regulations, a lack of technical expertise and a lack of funding are the main barriers to the development of solar energy in Pakistan. This study recommends the need for a comprehensive national policy for the development of solar energy, as well as increased investment in research and development, to fully harness the potential of solar energy in Pakistan. Several provincial governments in Pakistan have invested in solar technology for groundwater pumping in agriculture. These development investments aim to promote the use of solar-powered irrigation pumps (SIPs) and provide incentives for farmers to shift from diesel- to solar-powered pumps. Some of these initiatives include subsidized schemes for SIPs, coupled with high-efficiency irrigation systems, to reduce the cost of installation and encourage the adoption of solar technology [35]. Therefore, while there may not be a national policy, there are efforts at the provincial level to promote and incentivize the adoption of solar technology for groundwater pumping in agriculture. Punjab has passed the Water Act 2019 [35], which explicitly mentions: "An Act to comprehensively manage and regulate water resources in Punjab in the interest of conservation and sustainability". The Punjab Irrigated Agriculture Productivity Improvement Project (PIAPIP) is currently the largest investment for groundwater pumping in agriculture. This project, sponsored by the Agriculture Department of Punjab through the World Bank, aims to stimulate the use of high-efficiency irrigation systems (HEIS) coupled with solar irrigation pumps (SIPs) through capital cost subsidies [36]. As a result of this program, there has been a district-wise spread of SIPs across Punjab, with the highest number of SIPs installed in the Rawalpindi division and the least number of SIPs installed in the Bahawalpur division. Figure 6 provides a visualization of this distribution. The Agency for Barani Areas Development (ABAD) has installed 83 solar pumps in different areas of the Soan Basin Potohar region of Punjab province. PARC has installed 374 solar pumps integrated with HEIS in different areas of the Soan Basin. The Sindh government has launched 11 schemes of Rs. 802 million to install solar-powered tube wells at subsidized rates to improve and strengthen the province's agriculture sector in 2017, but the progress of this scheme is still unknown. Baluchistan has installed 160 solar-powered drip irrigation systems in the command area (130 ha) of Zhob and Mula rivers. The government of Khyber Pakhtunkhwa (KP), from 2015–2016, also gave incentives to farmers of 50% cost sharing for solar pumps in rainfed areas of the province. The irrigation department of KP installed solar pumping systems at ten selected sites as a pilot scheme in 2016–2017 [4].

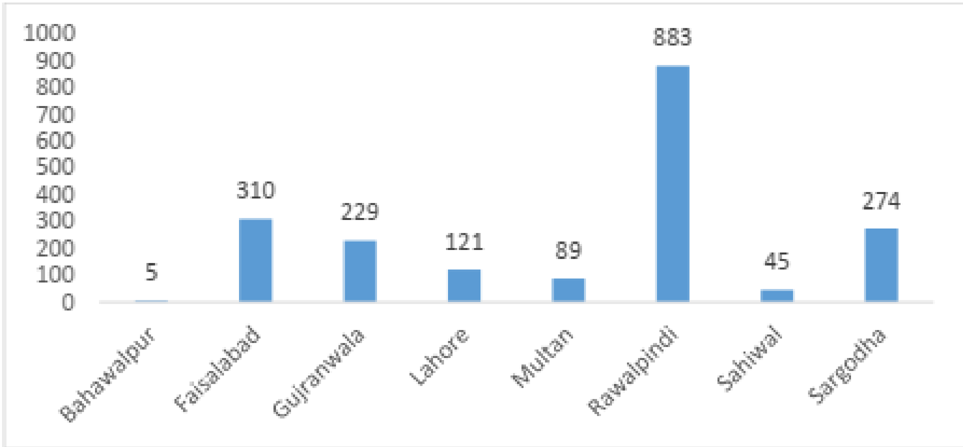

Figure 6. District-wise SIPs in Punjab.

5. A Case Study on Solar-Powered HEIS

A field study was conducted to evaluate the social and economic impact of solar-powered HEIS installed under the "Promotion of High Value Agriculture through Provision of Climate Smart Technology Package" project throughout Punjab, Pakistan. For this purpose, an intensive on-site survey was performed at 84 sites for the collection of data regarding sites where solar-powered HEIS were installed under the said project, sites where diesel- or electric-powered HEIS is practiced and sites where flood irrigation is used. The quantitative results of solar-, diesel- and electric-powered HEIS and flood irrigation methods were compared to evaluate the socio-economic impact of solar-powered HEIS.

Under the said project, more than 2100 sites with solar-powered HEIS on subsidy schemes were completed on 20,000 acres of land in Punjab, Pakistan. A total of 84 sites were selected from these sites for the evaluation of solar-powered HEIS, an investigation of saving in energy costs (i.e., liters of diesel/watts of electricity saved), a measure of the reduction in irrigation costs as compared to conventional power (diesel and electricity), an evaluation of the reduction in CO_2 emissions and to investigate the water productivity increase.

A questionnaire form consisting of farmer details, irrigation practices (HEIS/flooding), the area under HEIS/flooding, water source, the energy source for irrigation (electricity/diesel/solar), input costs, revenues and farmer's satisfaction was used for obtaining the primary data during the survey. Out of the 84 farm sites, 24 farmers with a total landholding of 2425 acres were practicing conventional flood irrigation to irrigate their lands. Among the group of twenty-four farmers, only one had access to sufficient canal water throughout the year. The remaining 11 farmers used diesel, and the remaining 12 used electricity to pump groundwater for flood irrigation. On the other hand, 60 farmers, with landholdings of 2367 acres, were practicing HEIS irrigation to irrigate their lands. Out of these sixty farmers, there were only eight farmers who were running their HEIS systems with electricity, while fourteen from the rest were using diesel and thirty-eight were using solar to run HEIS.

The average size of farm sites practicing solar-powered HEIS irrigation was 10 acres. On average, the installed solar systems had a capacity of 9 kWp to match with 8.5 hp (horsepower) pumps. The average calculated cost of a PV system per acre was 0.143 million PKR, whilst the per kWp cost was 0.15 million PKR. Although the initial cost of a PV system was relatively high, the low operational costs make it a feasible solution for farmers to adopt. The statistics of surveyed farm sites showed that the farmers with small to medium landholdings (60 farmers with 2368 acres) were growing high-value crops and preferred HEIS systems for precision in irrigation. Moreover, it was recorded during the field surveys that 53 out of 84 farm sites had grid connections in the vicinity. This was also evident from the farmer's statistics that 38 farmers had adopted HEIS systems after being offered solar as compared to 14 farmers operating HEIS with diesel.

To carry out the cost comparison of pumping systems powered by solar, diesel and electric, a comparison of 7.46 kW power pumping systems operating on electricity, diesel and solar systems was performed. The unit cost of solar was found to be PKR. 18.29, which was 4% less than the subsidized electric cost and 66% less than the unsubsidized diesel cost, respectively. The information collected during farmer interviews was analyzed to quantify the consumption of diesel for operating HEIS and flood irrigation. According to the analysis, on average, 330 L of diesel were consumed per acre annually for operating HEIS, while for flood irrigation, the consumption was higher, at 731 L per acre annually. HEIS consumes 55% less diesel as compared to flood irrigation. A 17.29 MWp solar power HEIS system has been installed for 20,000 acres of land in this project, resulting in an annual saving of 6.6 million liters of diesel. This saving in fuel corresponds to a 726 million PKR saving per year in the import bill of diesel.

It was analyzed that 4863 m^3 of water was consumed per year for flood irrigation of an acre of land throughout the year on average, while the amount was reduced to 2879 m^3 when irrigating through HEIS. HEIS resulted in a 41% water saving as compared to flood irrigation. Regarding the increase in farmers' income, 46 out of 64 HEIS farmers and 18 out of 24 flood irrigation farmers shared their information. The average profit was 165,611 PKR per acre and 333,464 PKR per acre for flood-irrigating and HEIS-irrigating farmers, respectively. This revealed that farmers using HEIS for irrigation earned a significant increase in income compared to those using flood irrigation, with a difference of 101%. This can be attributed to the fact that farmers using HEIS typically grow high-value crops, while those using flood irrigation grow conventional crops, resulting in lower income.

The widespread adoption of solar technology can have a substantial impact on reducing the consumption of fossil fuels as well as the associated environmental impacts. When compared to conventional energy sources, solar energy technologies offer significant environmental benefits and contribute to sustainable development. Therefore, the utilization of solar energy at a local level can bring about positive environmental implications, including the reduction of CO_2 emissions. The reduction in diesel usage has led to a decline in annual CO_2 emissions of 0.88 tons per acre per annum as 1 L of diesel emits 2.67 kg of CO_2 gas per year. For 20,000 acres, a reduction in CO_2 emissions was estimated at 17,622 tons per year.

A total of 38 farmers were operating HEIS using the solar system and information regarding farmer satisfaction was analyzed using interview data; 66% of farmers were highly satisfied, while 31% were satisfied with the solar-operated HEIS system and recommended it to their fellow farmers. The results showed that all the farmers were content with the performance of their solar systems in meeting the irrigation needs of their crops, with all of them reporting high satisfaction levels. Half of the farmers reported that they had achieved excellent yields, and 39% reported an increase in their crop yields compared to their previous yields, indicating their satisfaction with the solar systems. Moreover, 71% of the farmers reported no operational costs after the installation of the solar systems, as shown in Figure 7.

The results of the impact assessment study indicated that the diesel consumption with HEIS for irrigating an acre per year is between 230–430 L per acre per annum for vegetables and orchards that can be eliminated in the case of solar pumps, thus saving 6.6 million liters, equivalent to 726 million PKR from 20,000 acres under the said project. This has shown a reduction in annual CO_2 emissions and it is estimated at as much as 17,600 tons per annum from 20,000 acres (i.e., 0.88 tons per acre per annum). A comparison of a 7.46 kW pumping system operating on electricity, diesel and the solar system showed that the unit cost of solar was found to be PKR. 18.29, which was 4% less than the subsidized electricity cost and 66% less than the unsubsidized diesel cost, respectively. The survey results show that HEIS saves 35% to 45% of water and the increase in the average income of the farmers practicing drip irrigation was estimated to be 101% higher than that of those practicing flood irrigation. The total cost for running the irrigation pumps is reduced to one third over its lifetime by replacing diesel as a main fuel with solar power.

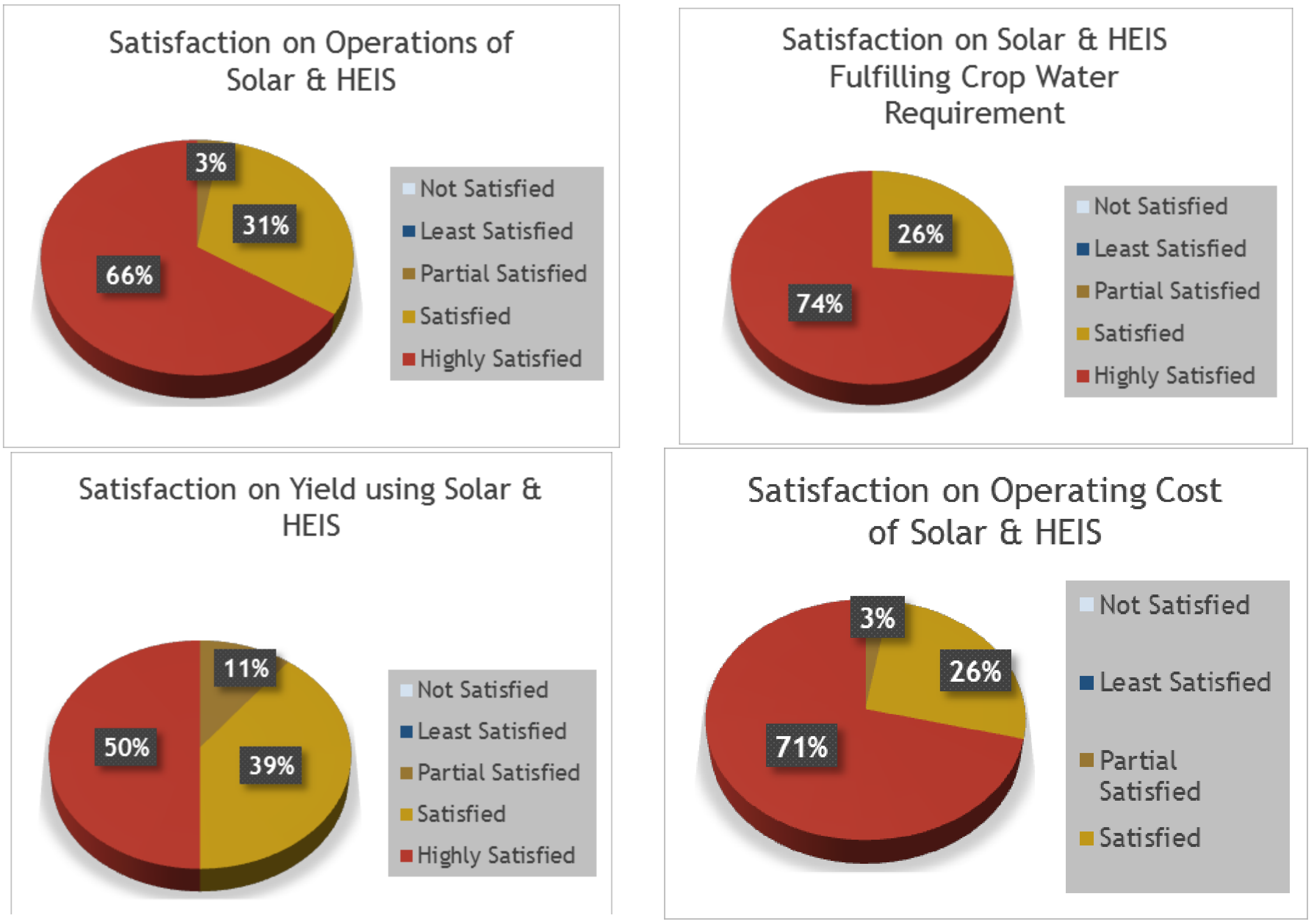

Figure 7. Farmer's satisfaction on solar-operated HEIS.

Based on the analysis of the energy and water situation in Pakistan and the cost benefit comparison presented in the study, it is recommended that the adoption of solar energy should be promoted for running high efficiency irrigation systems. This would not only help reduce the consumption of fossil fuels and associated environmental impacts, but also increase farmers' income and reduce their operational costs. Moreover, the use of solar-powered irrigation systems can improve crop yields, leading to food security and poverty reduction. Thus, the government and policymakers should consider implementing policies and incentives to encourage the large-scale adoption of solar energy in the agricultural sector.

6. Solar-Powered Irrigation System Planning, Design and Suitability

Solar-powered irrigation system (SPIS) planning, design and suitability is an important strategy to meet crop water requirements according to irrigation scheduling in a cost-effective way by selecting different system components. The design criteria for SPIS can be (i) peak crop water requirement and (ii) the lowest solar energy availability in a year. Crop water requirement changes with crop development and weather conditions, and the first criteria-based approach is an easy method by which to start SPIS design. For an effective SPIS design, following information and knowledge are key measures that must be known before start the process.

- Electrical circuit knowledge
- Pipe hydraulics knowledge
- Crop water requirement
- Irrigation scheduling
- Market updates

Figure 8 illustrates the various data that need to be considered when designing a complete SPIS. These include weather data, water source, soil data and crop data, which are used to determine the crop water requirement (CWR) at the specific site. The CWR is then used to select the appropriate PV pumping system based on the location, water source and weather data of the site.

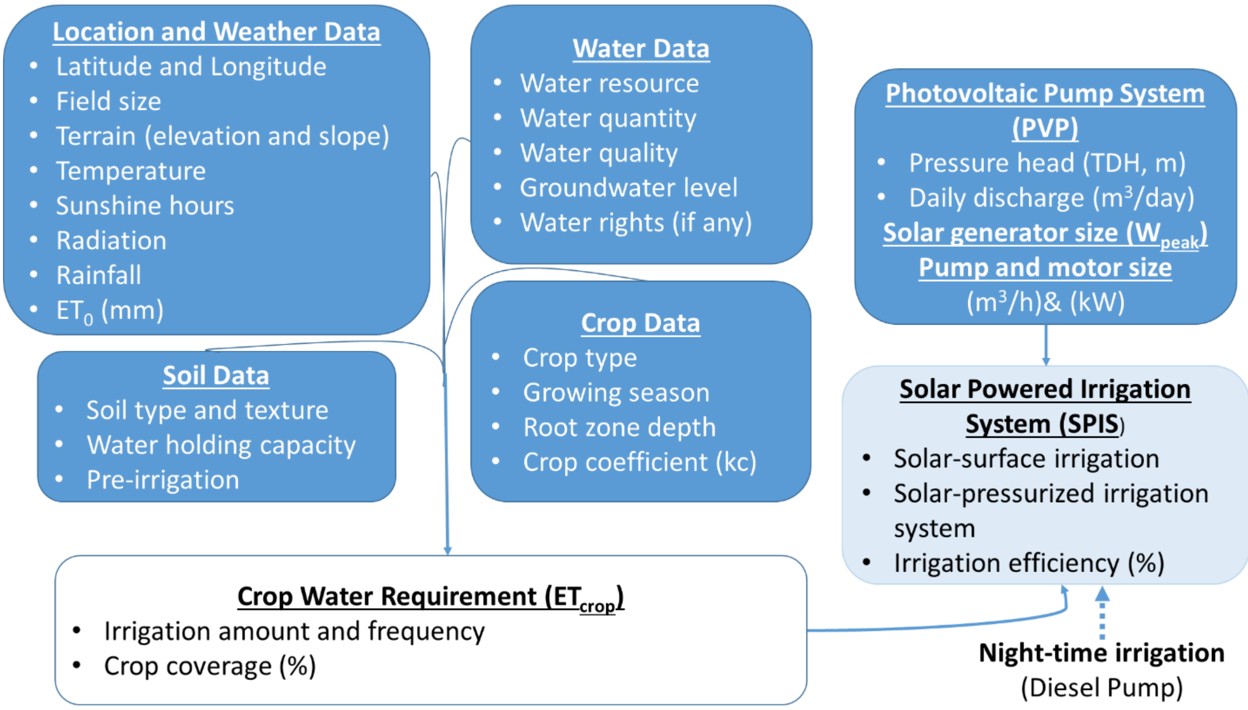

Figure 8. The data and steps required for planning and designing of SPIS.

After determining the peak crop water requirement, there is a need to investigate the source of water, i.e., either groundwater or surface water such as ponds/mini dams, etc. Then, it is required to calculate the peak solar hours (solar insolations) for incident solar radiation of 1000 watt/m^2. This is calculated by adding all-day radiations received each hour and dividing it by 1000. The design flow rate of the pump in gallons per minute (gpm) is calculated by a formula. Q (gpm) = Peak crop water requirement (gallons per day)/(peak solar hours $\times$ 60). The total dynamic head (TDH) is the total amount of energy required to move water from one point to another in the piping system. It is the sum of the static head, the friction head and any additional losses or gains in the system. The static head is the vertical distance between the source to the delivery point, and the friction head is calculated using the Darcy-Weisbach equation. A minimum minor loss of one foot should be considered for designing purposes [10]. In solar-powered HEIS systems, the operating pressure requirement is 15 psi, which means 33 feet of additional head has to be added for TDH calculations. After calculations of the design flow rate (in gpm) and TDH (in ft), pump selection can be determined via pumping curves or tables provided by manufacturers. The pump horsepower, called break horsepower (BHP), is calculated using the formula [BHP = (Q × TDH × SG)/(3960 × eff)], where SG is the specific gravity of water and eff is the pump efficiency. The motor horsepower is calculated by dividing BHP with motor efficiency. Then, design a solar system for the motor's actual horsepower. After the calculation of the power required to run the motor and pump, the selection of a PV solar panel and its array size (in peak wattage (Wp)) is performed using specification tables provided by the manufacturers. It is general practice to oversize the PV panel array by 20% to account for mechanical and electrical losses in the system. In addition, it should be increased by another 25–30% to reduce dirt and temperature effects, if a cleaning and cooling system for the PV panel is not installed. A typical solar-powered pumping system consists of the following components (Figure 9).

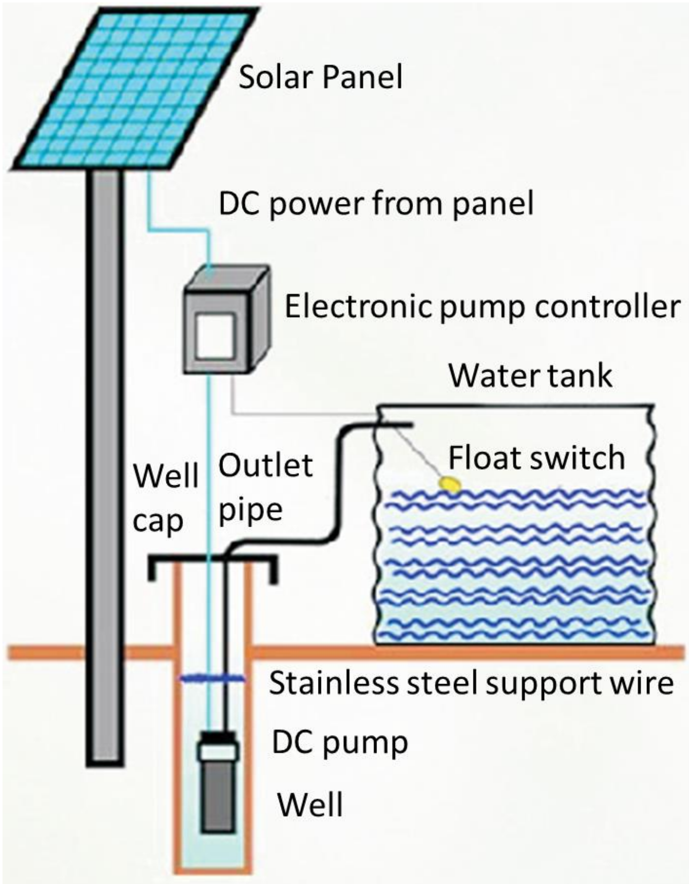

Figure 9. A typical solar-powered pumping system (adopted from Saleem and Ashraf [15]).

The pumping unit consists of a submersible DC pump and a motor of size 12 to 24 volts for small systems and 250 volts and over for large-scale units. The selection of the pumping unit should be carefully carried out because it directly influences the total cost of the solar system. Solar PV panels provide the required power to the pumping unit. On the market, different types of solar panels are available, such as poly crystalline (12–14% efficient), mono crystalline (16–19% efficient) and amorphous-type thin films (7–8% efficient). These panels of 12 to 48 volts produce rated power from 50 Wp to 260 Wp under standard operating conditions (i.e., incident solar radiations = 1000 watt/m^2 and the cell temperature remains around 25 °C). The pump controller is a stabilizer, which is a necessary component and is required to stabilize the output power fluctuation due to continuous change in incident solar energy throughout the day. The direction and tilt angle of the PV array should be at a right angle to the Sun's rays for maximum power output. Therefore, the south facing direction of the PV surface is most useful for harnessing the solar energy. For large-scale irrigation projects, the tilt angle is set equal to the latitude of the proposed site for year round best performance. For a medium-sized project, the tilt angle is set according to the seasonal changes for best solar performance; i.e., during the summer season, the tilt angle is set equal to latitude -15° and during the winter season, the title angle is set equal to latitude $+15^{\circ}$. For a small-scale system, sun tracking throughout the day is used, called a traceable/trackable PV array structure.

A suitability study can help to determine the feasibility and potential benefits of this technology in a specific location. The study should consider several factors, such as:

Solar Radiation: The availability and intensity of solar radiation are important factors in determining the suitability of solar-powered irrigation systems. The study should measure the solar radiation in the area over a period of time to assess the potential for energy generation.

Water Demand: The study should also consider the water demand for irrigation in the area, as this will impact the size and capacity of the solar system required.

Soil and Climatic Conditions: The study should take into account the soil and climatic conditions in the area, as these can affect the types of crops that can be grown and the irrigation requirements.

Economic Feasibility: The study should assess the economic feasibility of on-farm solar systems for drip irrigation by analyzing the costs and benefits of the technology, including the savings on energy costs, the potential for increased crop yields and the return on investment.

Technical Feasibility: The study should also consider the technical feasibility of on-farm solar systems, including the availability of equipment and spare parts, the skill level of local technicians, and the availability of technical support.

Environmental Impact: The study should also consider the environmental impact of on-farm solar systems for irrigation, including the reduction of greenhouse gas emissions and the conservation of water resources.

By conducting a suitability study of solar-powered irrigation systems, farmers and stakeholders can gain a better understanding of the potential benefits and challenges of this technology in a specific location. This can help to inform decision-making and investment in this technology.

7. Solar-Powered Irrigation System (SPIS) Benefits, Risks, Challenges and Opportunities

SPIS have many advantages for farmers in terms of easy access to water and improving agricultural productivity. SPIS have the potential to be used in various settings, including both large-scale and small-scale irrigation systems. This is because solar energy can be harnessed and used to power irrigation systems in areas that are not connected to the main power grid. This makes it a viable option for decentralized irrigation systems in remote areas. Additionally, the scalability of solar technology means that it can also be used for larger-scale irrigation systems in more developed regions.

- It is a clean and green low-carbon irrigated system
- It is easy to use in remote areas with unreliable access to electricity
- It reduces energy costs for irrigation

SPIS is a reliable and affordable source of energy for irrigation, particularly in rural areas where access to the electricity grid is limited. By using solar energy to power pumps for irrigation, SPIS can reduce greenhouse gas (GHG) emissions associated with conventional diesel or electric pumps. SPIS are also climate-friendly, providing an alternative energy source that can help reduce emissions from agriculture [3].

Solar-powered irrigation systems have gained attention in recent years as a sustainable and cost-effective alternative to traditional irrigation methods. The use of solar energy to pump water for irrigation can provide a reliable source of water, even in remote and off-grid areas, and can help to reduce the environmental impact of irrigation. One of the main benefits of solar-powered irrigation systems is their cost-effectiveness. Solar-powered irrigation systems can provide significant cost savings compared to traditional irrigation systems that rely on fossil fuels. The payback period for a solar-powered irrigation system is typically 3 to 5 years, which is much shorter than for traditional systems. Solar-powered irrigation systems are also reliable and can operate independently of the electrical grid. Solar-powered irrigation systems can provide a reliable source of water for irrigation, even in areas with limited access to the national grid. This can help to improve crop yields and reduce water waste. In addition, solar-powered irrigation systems can help to conserve water by providing precise control over the amount and timing of water application, improving water use efficiency and reducing water loss, which can help to conserve water resources.

Solar-powered irrigation systems offer several benefits for farmers. Some of the main benefits include:

Cost Savings: Solar-powered irrigation systems can provide significant cost savings compared to traditional irrigation systems that rely on fossil fuels. The cost of fuel and maintenance is eliminated, and the systems can be designed to be self-sustaining.

Reliability: Solar-powered irrigation systems are reliable and can operate independently of the electrical grid, making them well-suited for remote and off-grid areas.

Water Conservation: Solar-powered irrigation systems can help to conserve water by providing precise control over the amount and timing of water application. This can improve crop yields and reduce water waste.

Environmental Benefits: Solar-powered irrigation systems do not produce greenhouse gas emissions and can help to reduce the environmental impact of irrigation.

7.1. Key Risks and Challenges

Solar-powered irrigation systems also have some risks and challenges that should be considered. One of the main risks is the high initial cost of the systems. During the case study, it was found that the high upfront costs of solar-powered irrigation systems can be a barrier for farmers, particularly smallholder farmers. Another risk is the maintenance and repairs of the systems. It was found that solar-powered irrigation systems require regular maintenance and repairs, which can be costly and time-consuming. In addition, access to spare parts and technical support for solar-powered irrigation systems may be limited in some areas, which can make it difficult to repair or replace components if they fail. Solar-powered irrigation systems also rely on the availability of sunlight, which can be affected by weather conditions such as clouds and storms. In addition, cultural and social factors may also play a role in the adoption of solar-powered irrigation systems. It was found that social resistance and cultural barriers can hinder the adoption of new technologies, which can make it difficult to introduce solar-powered irrigation systems in certain areas. It was found that small-scale farmers were met with difficulties in accessing financial support and accessibility to good quality products and services.

SPIS provides affordable and reliable energy for irrigation and there is no cost per unit of power once the systems are installed. On the other side, there is no such specific policy on groundwater pumping using solar technology for irrigation, which is leading to the over-abstraction of groundwater. Furthermore, farmers are selling water to their neighbors at a profit, increasing overall water withdrawals. To ensure the sustainable use of SPIS technology, it is crucial to recognize water-related risks at the financial and design stages. Incentives for farmers to save on fuel or electricity costs for water pumping should also be introduced. Capacity development activities are required to ensure that users have a basic understanding of the set-up and functions of the system, and can manage its daily operation and maintenance. Without proper management and regulation, there is a risk of unsustainable water use. Figure 10, adapted from a World Bank report, shows the potential and challenges of solar water pumping, which can be used as a guideline for the situation in Pakistan.

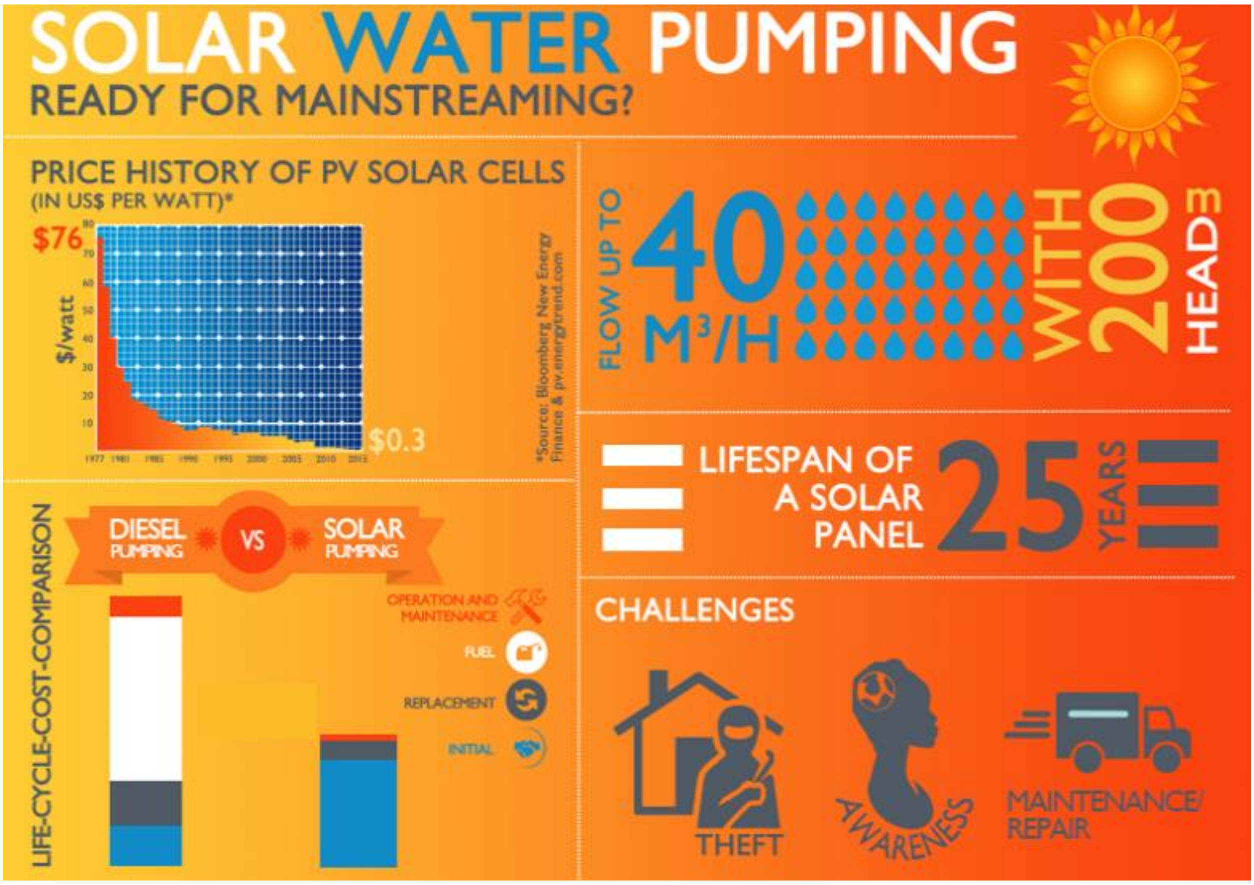

Figure 10. A summary of the potential and the challenges of solar water pumping [37].

Solar irrigation has the potential to significantly improve agricultural productivity and water management in Pakistan. During the case study, presented in Section 5, the high operational cost was identified as one of the reasons for the slow adaptation of solar-powered HEIS. Some key issues and challenges were identified that must be addressed to fully realize it's potential.

- Higher capital cost as compared to conventional diesel pumps remains a challenge for farmers to contribute their share.
- It has been observed that some solar systems are being used for groundwater pumping that is subsequently used for flood irrigation to the same crop or other crops grown at the farms.
- The capacity of technicians and labor needs to be built up to handle the solar equipment.

High Cost of Equipment and Installation: One of the main issues facing solar irrigation in Pakistan is the high cost of the equipment and installation. Many farmers in Pakistan lack the financial resources to invest in solar irrigation systems, and there is a need for more affordable and accessible solutions. Farmers are facing challenges in investing in solar-powered pumping systems due to the high initial costs compared to diesel-powered pumps. Additionally, solar-powered pumps have lower discharge capacities, making them less suitable for some irrigation applications. The costs of solar-powered pumping systems also significantly increase with an increase in pumping depth and discharge. In particular, for depths greater than 100 feet, the cost of solar tube wells becomes uneconomical. These factors make it difficult for some farmers to adopt solar-powered irrigation systems.

Lack of Awareness and Knowledge: Another key issue is the lack of awareness and knowledge regarding solar irrigation among farmers. Many farmers in Pakistan are not familiar with the benefits and potential of solar irrigation, and may not know how to properly operate and maintain these systems.

Reliability and Durability: In addition, there are also challenges related to the reliability and durability of solar irrigation systems in Pakistan. The harsh environmental conditions and lack of maintenance can lead to frequent breakdowns and repairs, which can be costly and time-consuming for farmers.

Maintenance and Repairs: Solar-powered irrigation systems require regular maintenance and repairs, which can be costly and time-consuming.

Limited Access to Spare Parts: In some areas, access to spare parts and technical support for solar-powered irrigation systems may be limited, which can make it difficult to repair or replace components if they fail. Additional challenges include the lack of awareness about the quality of PV and the benefits of high-quality products.

Weather Dependence: Solar-powered irrigation systems rely on the availability of sunlight, which can be affected by weather conditions such as clouds and storms. SIPS operating hours are limited per day and farmers are a somewhat reluctant to use it for flood irrigation.

Social Acceptance: In some cultures, the adoption of new technologies can be hindered by social resistance, which can make it difficult to introduce solar-powered irrigation systems. The majority of irrigation is carried out through flood irrigation, and many farmers are hesitant to switch from this traditional method to high-efficiency irrigation systems (HEIS) using solar power. Additionally, around 66% of farmers have small landholdings under 25 acres, and installing solar panels for SPIS requires additional land area, which can be a challenge for these farmers.

Lack of Infrastructure and Limited Access to Investment: Pakistan has significant solar energy potential, but needs more infrastructure to capitalize on this potential. The country has abundant solar resources, but needs more transmission capacity to move these resources to market. Additionally, the Pakistani government is often reluctant to invest in renewable energy due to concerns about grid reliability. However, if Pakistan can overcome these challenges, its renewable energy sector could be a significant player in the global market.

Political Instability: Pakistan faces several political instability issues that could prevent it from fully embracing renewable/solar energy. Instability in the northwest, where most of Pakistan's solar energy potential is located, has hindered investment in the sector. Political instability also affects the country's ability to collect revenue from its solar industries. Despite these challenges, there are several reasons why Pakistan should focus on solar energy as an essential part of its overall policy agenda. Renewable energy can provide much-needed employment and income opportunities for the country's poorest residents, help reduce greenhouse gas emissions and provide security against dependency on foreign oil supplies.

Technical Barriers: Solar energy is a reliable, sustainable source of electricity. One of the main challenges is that these technologies are only sometimes efficient. For example, solar panels need sunlight to work, but the sun does not always shine in Pakistan. Solar power plants need to be built with a lot of backup power; if the sun is not shining, they can switch to using other energy sources such as coal or gas. One of the concerns regarding the scaling up of solar irrigation programs in Pakistan is the potential for the over-exploitation of groundwater resources. This is because the availability of energy alone is not enough to ensure sustainable water use; the capacity of the irrigation system also plays a significant role.

Despite these challenges, there have been some notable successes in the use of solar irrigation in Pakistan. For example, a study by the International Water Management Institute (IWMI) found that farmers who used solar irrigation systems were able to increase their crop yields by up to 50% [38]. This increase in crop yields can lead to an increase in income for farmers, which can help to improve their livelihoods. Additionally, solar irrigation can also help to improve water management in agriculture. With increasing water scarcity and demand, solar irrigation can help to reduce water use and improve water efficiency in agriculture. A study [39] found that solar irrigation systems can reduce water use by 30–40% in comparison to traditional irrigation methods. Moreover, there is also a significant potential for solar irrigation to improve water management in Pakistan. With increasing water scarcity and demand, solar irrigation can help to reduce water use and improve water efficiency in agriculture.

7.2. Opportunities

Being cost and climate efficient, the sector of solar energy, which is now at a nascent stage in Pakistan, holds huge potential for development. The Alternate Renewable Energy Policy of Pakistan aims to increase the share of renewable energy in the national power grid from 5% to 20% by 2025 and 30% by 2030. The Pakistani government has supported renewable energy development in recent years, intending to increase its energy independence. There are several opportunities for solar energy development in Pakistan. Pakistan is one of the most solar-rich countries in the world. It has ample sunlight and good weather conditions to generate solar energy. Solar power has been recognized as a renewable energy source with high potential for economic development, environmental protection and social equity. The country's sunny climate and ample sunlight make it an ideal location for solar power installations. By harnessing these resources, Pakistan can continue to provide reliable and affordable electricity to its citizens while helping to reduce greenhouse gas emissions. In essence, the solar energy landscape in Pakistan is full of potential. Despite the numerous challenges facing the sector, many opportunities can be taken to develop the sector further and create a more sustainable energy future for the country. Government policies, technological advancements and public-private partnerships all have a role to play in helping to move the solar energy sector in Pakistan forward. Pakistan has vast PV potential, 5 to 7 kWh/m^2 of solar energy can be produced using around 3000 sunlight hours per year [40]. Exploiting this available solar energy for irrigation will increase crop productivity and food security, and help in attaining cleaner and more sustainable food production. A scheme may be financially viable for farmers if the high initial capital cost of replacing diesel or electric tube wells with solar tube wells or installing new solar tube wells can be appropriately subsidized.

As the cost of diesel and grid supply tariffs continue to rise, solar pumping is becoming an increasingly attractive solution. The cost of a Lorentz solar pump for irrigating 10 acres of land in five days is approximately Rs. 1,350,000, which includes the pump, motor, solar panels, pump controller, piping and plumbing up to pump delivery. For irrigating 20 acres of land in the same timeframe, the cost is about Rs. 2,575,000. If farmers were allowed to pay for these systems in 36 equal installments, they would be more likely to invest in solar pumps, which could revolutionize land irrigation, increase farm yields, boost the country's GDP and reduce waterlogging. However, the slow growth of the solar pumping market can be attributed to the 100% up-front payment cost [41].

Opportunities are unlimited and challenges are many in SPIS technology. The biggest challenge is the unavailability of a groundwater pumping policy using SPIS technology and its implementation. The other challenges are subsidies, net metering policy, lack of renewable energy education and skills development training, etc. To promote the growth of solar technology in Pakistan, it is necessary to provide education regarding solar technology. Currently, there is a lack of solar education in the country, which is a hindrance to the growth of solar technology. To address this issue, technical educational institutes, schools, colleges and universities should introduce solar diplomas and degree courses. This will create a pool of educated professionals who can fill the huge demand gap for skilled manpower in the solar industry.

8. Conclusions and Recommendations

8.1. Conclusions

- Solar energy has the potential to revolutionize the agricultural sector in Pakistan by providing a cost-effective, reliable and sustainable source of energy for irrigation.

- The results indicate that Pakistan has a substantial potential for photovoltaic power, with a yearly sum of global horizontal irradiation of 1300 to 2300 kWh/m^2, providing 1200 kWh/kWp to 2100 kWh/kWp per year
- Solar pumps in conjunction with HEIS should be promoted because they are much cheaper than the electricity (4%) and diesel (66%) operated systems and result in significant water saving (41%).
- The payback period for a SPIS is typically 3 to 5 years, and solar system design should be according to motor actual horsepower.
- Scaling up SPIS can meet clean energy targets and provide assured irrigation to the farmers, but there is the threat of groundwater over-exploitation because there is no specific national policy on solar technology for groundwater pumping in agriculture. Solar pumps have the potential to mitigate CO_2 emissions, but they can also contribute to groundwater over-exploitation.
- However, the adoption of solar-powered irrigation systems (SPIS) has been slow due to barriers such as the lack of awareness and knowledge, the lack of access to finances and the lack of technical expertise. It was found that the high upfront costs of SPIS is the key barrier for farmers, particularly small landholders.
- SPIS require regular maintenance and repairs, which can be costly and time consuming. In addition, access to spare parts and technical support for SPIS may be limited in some areas, which make it difficult to repair or replace components if they fail.
- Addressing these key issues and challenges will be crucial to unlocking the potential of solar irrigation in Pakistan, as well as achieving sustainable agriculture and water management.

8.2. Recommendations

- To promote sustainable agriculture and improve energy access for farmers, the government and other organizations need to work together to provide subsidies, financial assistance and technical support to farmers to purchase and install solar irrigation systems.
- Policymakers must develop and implement effective management plans and policies to replace existing diesel-powered pumps with solar pumps and prevent excessive groundwater abstraction.
- More research and development are necessary to improve the efficiency, reliability and durability of solar irrigation systems and to develop low-cost and easy-to-maintain systems that are suitable for small landholders.
- Precision irrigation techniques should be employed to optimize the performance of SPIS.
- Explore innovative financing models such as microfinance and leasing to make solar irrigation more accessible and affordable for smallholder farmers.
- Develop and implement policies and regulations that support the adoption of solar irrigation, including subsidies and incentives for solar-powered pumps and irrigation systems.
- Increase awareness and knowledge about solar irrigation among farmers and stakeholders through targeted outreach and education programs.
- The government should raise awareness and knowledge among farmers to encourage the adoption of solar irrigation systems and must support and invest in the development and promotion of solar irrigation systems in the country.
- Foster partnerships and collaborations between the public and private sectors to promote research and development, knowledge sharing and technology transfer in the field of solar irrigation.

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