



Design and Techno-Economic Evaluation of a Solar Photovoltaic Groundwater Pumping System for Irrigation and Rural Water Supply in Punjab, India

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Abstract: Diesel-powered groundwater pumping remains common in Indian agriculture, contributing to high fuel use, costs, and greenhouse gas emissions. With rising irrigation demand and groundwater stress, an accelerated transition to low-emission irrigation technologies is increasingly urgent. This study assesses the technical and economic feasibility of replacing diesel-powered pumping with a solar photovoltaic (PV) system in Punjab, India. A 10 kWp PV system was found to reliably meet irrigation demand for one hectare of paddy cultivation and typical domestic water needs under seasonal variability. Life Cycle Cost and Break-Even analyses over a 15-year horizon show substantially lower costs than diesel pumping, with a break-even point in the first year under a replacement scenario. The PV system also reduces operational emissions by approximately 4.6 t CO₂e per rice growing season, supporting sustainable irrigation transitions in groundwater-dependent regions.

Keywords: Diesel pump replacement; Groundwater irrigation; Punjab India; Solar photovoltaic pumping; Techno-economic assessment.

Introduction

India's agricultural sector accounts for approximately 16.5% of national electricity consumption, largely driven by groundwater irrigation (Bureau of Energy Efficiency, 2024). Irrigation pumps – around 21 million units, including both diesel- and electricity-powered systems – contribute significantly to energy use and greenhouse gas emissions, estimated at 8–12% of India's total emissions (Daccache et al., 2014; Qin et al., 2024; Rathore et al., 2018). High fuel and maintenance costs associated with diesel pumps (Terang & Baruah, 2023; Xie, 2025; Zhu et al., 2024), combined with limited grid access in rural areas, highlight the need for alternative energy solutions, positioning solar photovoltaic irrigation pumps as a viable option.

Punjab, located in northwest India, is a key agricultural state that produces over 10–12% of India's rice despite accounting for only about 3% of the country's cultivated area (Prabhjyot-Kaur et al., 2025). Rapid expansion of rice cultivation, particularly in districts such as Ludhiana, has significantly increased irrigation demand. Rice cultivation in Punjab requires approximately 120–150 cm of water per growing season, placing substantial pressure on groundwater resources (Sidhu et al., 2021).

Amid rising irrigation demand, groundwater stress, and energy dependence in Punjab, India has begun transitioning from diesel-based to solar-powered irrigation systems as part of broader efforts to improve water–energy–food sustainability (Yupanqui et al., 2025). National initiatives such as PM-KUSUM, along

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with state-level programs including Punjab’s Pani Bachao Paisa Kamao (PBPBK) scheme, have accelerated the adoption of solar photovoltaic water pumping systems by reducing reliance on diesel pumps, particularly in off-grid rural areas (Bureau of Energy Efficiency, 2024). While solar-powered irrigation offers clear advantages in terms of reduced operating costs and emissions compared to fossil-fuel-based pumping, its long-term sustainability depends on continued policy support, farmer participation, and effective groundwater governance to prevent over-extraction (Rathore et al., 2018; Watto et al., 2024).

While previous studies have examined the technical performance of groundwater pumping systems or the potential benefits of solar-powered irrigation (Bhatia & Singh, 2024; Nazir & Ashraf, 2024; Satpute & Singh, 2024), comprehensive comparative assessments remain limited. There is a lack of studies that systematically compare diesel-powered and solar photovoltaic groundwater pumps in terms of power requirements, life cycle costs, and greenhouse gas emissions at a clearly defined operational scale. Moreover, few analyses evaluate these trade-offs for a representative rural application, such as irrigation for one hectare of paddy cultivation combined with domestic water supply, under seasonal solar variability in high groundwater-stress regions like Punjab. This methodological gap limits the availability of practical and transferable evidence to support sustainable irrigation and energy planning.

Method

This study assesses the technical and economic feasibility of replacing diesel-powered groundwater pumping with a solar photovoltaic (PV) system in Punjab, India. The methodological framework is summarized in Figure 1, which outlines the sequence from system boundary definition to technical performance assessment and economic evaluation. The system boundary represents a typical rural application, consisting of irrigation for one hectare of paddy cultivation and domestic water demand for approximately 200 residents.

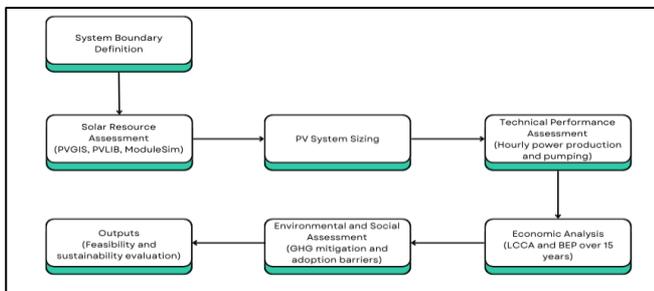


Figure 1. Methodological framework of the study

Solar resource assessment, PV system sizing, and technical performance evaluation were conducted using PVGIS data, processed through the PVLIB library and ModuleSim simulations, to account for seasonal variability in solar availability. The resulting system configuration was evaluated economically using Life Cycle Cost Analysis (LCCA) and Break-Even Point (BEP) analysis over a 15-year project horizon. Key technical and economic parameters used in the analysis are summarized in Table 1.

Table 1. Parameter Settings for Economic Analysis

Parameter	Value	Unit
Project horizon	15	Year
PV water pump capacity required	10	kW
Diesel capital cost	0*	USD
Diesel fuel	0.97	USD
Diesel price inflation rate	6**	%
PV water pump capital cost	5397.89***	USD
Discount rate	6	%
MPPT	649.87***	USD
DC Pump	383***	USD

* Assumed zero (pre-existing infrastructure)
 ** Adopted from Anusree and Sarika (2022)
 *** Calculation based

Result and Discussion

Technical Performance

Punjab experiences approximately 14 hours of daylight during the summer solstice and about 10 hours during the winter solstice. Simulation results show that a south-facing tilt angle of 27° maximizes annual energy production, slightly lower than the latitude-based estimate of 30.9° (Figure 2). Increasing the tilt angle to enhance winter performance improves seasonal output but reduces total annual generation, highlighting a trade-off between winter reliability and overall energy yield (Adiyasuren & Dei, 2019; Kaldellis et al., 2012; Ruan et al., 2024).

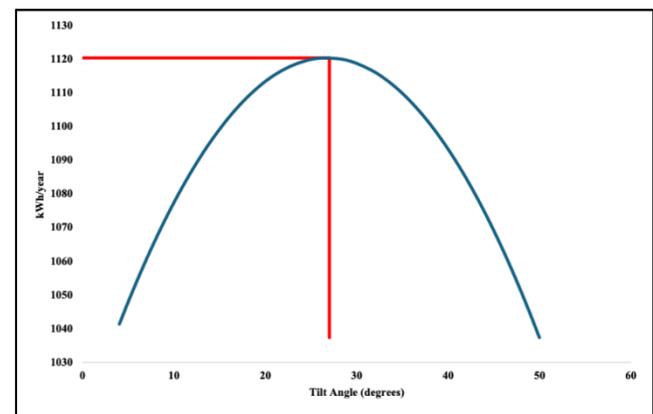


Figure 2. Optimal inclination angle for solar panels in Punjab

The PV system was designed to meet combined daily water demands of approximately 166,700 liters for irrigation and 11,000 liters for domestic use. A 10 kWp PV system coupled with a 4.84 kW pump was sufficient to meet demand even during low-irradiance winter conditions. On a representative day in December, the system pumped approximately 423 m³ of water, demonstrating adequate performance under conservative solar availability scenarios (Figure 3). Key technical parameters are summarized in Tables 2 and Table 3.

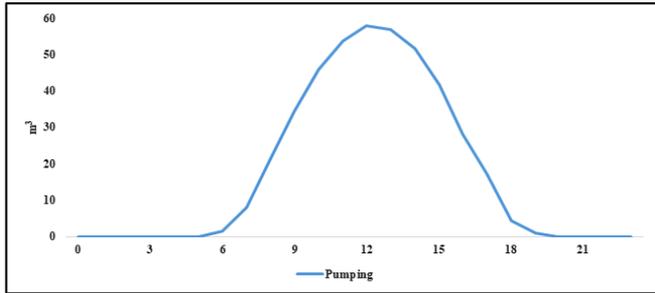


Figure 3. Hourly pumping profile of a 4.84 kW groundwater pump on a representative December day (total: 423 m³)

Table 2. Parameter Settings for PV Sizing

Parameter	Value	Units
Panel Efficiency	22	%
Panel Area	2.665	m ²
Panel Power	500	W
Number of Panels	20	-
Pump Efficiency	50	%
Water Density (ρ)	1000	kg/m ³
Gravity (g)	9.81	m/s ²
Total Lift Head	30	m
Daily Irrigation Demand	166,700	liters
Daily Drinking Demand	11,000	liters
Tank Capacity	400	m ³
Operating hours	6	hours
Average Insolation	3	kWh/m ²
Inefficiencies	20	%
Flowrate	0.008	m ³ /sec
Pump capacity	4.84	kW
PV Size	10.00	kWp

Table 3. PV array configuration and its detail

PV Array Configuration	Details
Panel Model	Trina DE18M 500W (42.8 Vmpp, 11.69 Amp)
Panels per String (Series)	4 panels
Strings in Parallel	5 strings
Total Panels	20 panels (5×4)
System Capacity	10 kWp (approx.)
MPPT Inputs	1 MPPT

System Configuration and Reliability

The selected system configuration consists of 20 monocrystalline PV modules arranged in series-parallel

strings, resulting in a total installed capacity of approximately 10 kWp. The MPPT controller was sized to accommodate array voltage and current limits (see Table 4), ensuring efficient power conversion and system protection. Manufacturer specifications indicate long operational lifetimes, low degradation rates, and resistance to harsh environmental conditions, supporting reliable long-term operation in rural applications.

Table 4. Array rating and determination of MPPT rating

Component	Rating
Each String Voltage	~171V (Vmpp), ~207V (Voc)
Each String Current	11.69A (Impp), 12.28A (Isc)
Array Voltage	~171V (Vmpp)
Array Current	~58.45A (Impp), ~61.4A (Isc)
MPPT Voltage Rating	≥171V
MPPT Current Rating	≥60A

Economic Performance

Life Cycle Cost Analysis results indicate a substantial economic advantage of the PV system compared to diesel-powered pumping. Over a 15-year project horizon, the PV system incurs a total cost of USD 242,122.58, whereas the diesel alternative reaches USD 2,841,949.57. The break-even point occurs within the first year of operation, primarily because the diesel pump is treated as pre-existing infrastructure and recurring fuel costs are avoided immediately under the replacement scenario (Figure 4).

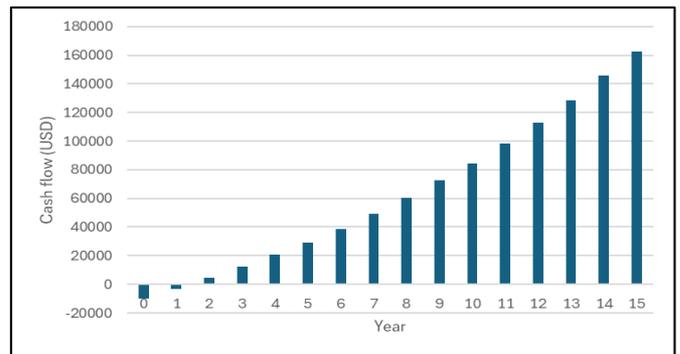


Figure 4. Break-Even Point Graph

Although the PV system requires higher upfront investment, its low operating and maintenance costs offset this initial expenditure rapidly. However, potential financial risks remain related to component reliability and long-term system performance, as discussed in previous studies (Shabbir et al., 2023; Zegait et al., 2022).

Environmental and Sustainability Implications

Replacing the diesel-powered pump with the PV system reduced operational greenhouse gas emissions

by approximately 4,617 kg CO₂e over a single 90-day rice growing season. While this represents a clear climate mitigation benefit, reduced pumping costs may increase groundwater abstraction if deployment is not accompanied by effective management measures, as observed in other regions (Balasubramanya et al., 2024; Bhatt & Kalamkar, 2017; Closas & Rap, 2017; Mekonnen et al., 2024).

Social and Policy Considerations

High upfront costs of solar irrigation systems may limit adoption by small, marginal, and women farmers (Durga et al., 2024; Kafle et al., 2022; Kumar et al., 2025). Evidence from Rajasthan suggests that inclusive eligibility criteria and targeted support mechanisms are necessary to ensure equitable access (Kishore et al., 2014). At the same time, solar irrigation systems can enhance livelihoods and promote women's economic empowerment, as demonstrated by pilot projects replacing diesel pumps with solar systems in Gujarat (NRDC International, 2018).

Conclusion

This study confirms the technical and economic feasibility of replacing diesel-powered groundwater pumping with a solar photovoltaic system in Punjab, India. For a representative application involving one hectare of paddy cultivation and domestic water supply for approximately 200 residents, a 10 kWp PV system was found to meet water demand reliably. The life cycle cost of the PV system over a 15-year period was estimated at USD 242,122.58, substantially lower than the USD 2,841,949.57 required for a diesel-powered alternative, with the break-even point occurring within the first year of operation.

The replacement of the diesel pump resulted in an operational greenhouse gas emission reduction of approximately 4,617 kg CO₂e over a single 90-day rice growing season. Beyond environmental benefits, the PV system reduces fuel expenditure and exposure to fuel price volatility, improving water supply reliability for rural users. These advantages can support livelihoods of small, marginal, and women farmers, provided that barriers related to upfront investment are addressed. Accordingly, targeted subsidies, inclusive financing mechanisms, and integration with groundwater governance and water-saving technologies are recommended to ensure sustainable deployment.

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Author Contributions

All authors made equal contributions to the conceptualization, methodology, analysis, and preparation of the manuscript. All authors reviewed and approved the final version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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