Solarisation of a Lift Irrigation System: Technical, Economic and Environmental Assessment of the Hriday Nagar Lift Pump Canal, Uttar Pradesh, India

Anil Garg (I.A.S.)[1], Shiv Prasad Maurya[2], Achyutanand[3], Sujeet Kumar Singh[4*]

[1]Principal Secretary, Irrigation and Water Resources Department, Government of Uttar Pradesh, India-226001, Email: garganil1971@gmail.com
[2]Chief Engineer Tubewell East Zone Ayodhya, Irrigation and Water Resources Department, Government of Uttar Pradesh, India-224123, Email: shivpmaurya@yahoo.co.in
[3]Superintending Engineer Tubewell Circle Gonda, Irrigation and Water Resources Department, Government of Uttar Pradesh, India-271001, Email: achyutanand.0047@gmail.com
[4]Executive Engineer, Tubewell Construction Division, Kanpur, Irrigation and Water Resources Department, Government of Uttar Pradesh, India-208004, Email: ee.barragemechvaranasi@gmail.com
*Corresponding Author: Sujeet Kumar Singh, Email: ee.barragemechvaranasi@gmail.com

Abstract
The Hriday Nagar Lift Pump Canal, located in Balrampur district, Uttar Pradesh, has been operational since 1968 and provides irrigation to approximately 166 hectares of agricultural land. For more than five decades, the canal relied entirely on grid electricity to operate its 20 HP pumping system. This dependence on conventional electricity presented persistent operational and financial challenges for the Uttar Pradesh Irrigation and Water Resources Department. Electricity expenditure increased substantially during peak irrigation periods, while frequent power interruptions disrupted scheduled water delivery. In addition, voltage fluctuations contributed to repeated motor-winding failures, increasing maintenance requirements, downtime, and operating costs. To address these limitations and improve the long-term sustainability of the irrigation system, the Hriday Nagar Lift Pump Canal was converted to solar-assisted operation under the Irrigation and Water Resources Department, Uttar Pradesh. A 25 kW on-grid solar photovoltaic (PV) power plant, integrated with a 25 kW Variable Frequency Drive (VFD), was installed to operate the existing pumping system efficiently while maintaining grid connectivity. This study evaluates the technical, economic, and environmental performance of the system following its solar conversion. Analysis of 11 months of post-commissioning electricity billing data demonstrates a substantial reduction in grid-energy expenditure. During the peak irrigation month of June, the electricity bill declined from approximately ₹19,200 to ₹6,200, representing a reduction of nearly 67.7%. annualised electricity-cost saving is approximately ₹65,945, based on the 11-month observation period., while the solar installation is estimated to avoid approximately 20 metric tonnes of CO_2 emissions annually. An important additional outcome is the improvement in the predictability of electricity expenditure. Following solar integration, monthly electricity bills have remained relatively stable at approximately ₹6,000–₹7,000, with considerably less seasonal variation than was observed under the earlier grid-dependent system. This improved cost stability is particularly relevant for government-operated irrigation infrastructure, where predictable recurring expenditure can support more effective budgeting and asset management. The findings are examined in the context of published research on solar-powered irrigation pumping systems and India's PM-KUSUM programme to determine the extent to which the Hriday Nagar experience is consistent with established evidence and where it provides additional practical insight. While previous studies have largely focused on theoretical energy potential, economic feasibility, farmer-level solar pumps, or programme-scale assessments, the present case study contributes actual month-by-month electricity billing evidence from an operational government lift irrigation canal. The Hriday Nagar case demonstrates that solar PV integration with existing lift irrigation infrastructure can reduce grid-energy expenditure, improve operational reliability, stabilize recurring electricity costs, and lower the carbon footprint of public irrigation systems without requiring replacement of the entire pumping infrastructure. The study concludes by identifying the technical, financial, operational, and institutional requirements necessary for replicating this model across other suitable lift canals and pumping installations in Uttar Pradesh, thereby supporting the transition towards more economical, reliable, and low-carbon irrigation infrastructure.

Keywords: Solar-Powered Irrigation, Solar Photovoltaic, Lift Pump Canal, Variable Frequency Drive, Sustainable Irrigation, Renewable Energy, Carbon Emission Reduction, Smart Irrigation, Solar Lift Irrigation

1. Introduction

Uttar Pradesh is one of India's leading agricultural states, where an extensive irrigation network plays a vital role in sustaining crop production and rural livelihoods. Lift pump canals form an important part of this infrastructure, particularly in areas where gravity-based irrigation is not technically feasible. Many of these systems were developed several decades ago and have traditionally depended on grid electricity for pumping. Over time, however, increasing electricity costs, interruptions in power supply, and voltage fluctuations have created significant operational and financial challenges. These problems become particularly critical during peak agricultural periods, when timely and reliable irrigation is essential for crop production. The Hriday Nagar Lift Pump Canal, located in Balrampur district of Uttar Pradesh, represents a typical example of such an ageing grid-dependent lift irrigation system. Commissioned in 1968, the canal lifts water from the Chakwa drain and provides irrigation to approximately 166 ha of Culturable Command Area (CCA). For more than five decades, its 20 HP pump operated entirely on conventional grid electricity. During peak irrigation months, particularly June and July, monthly electricity expenditure reached approximately ₹19,000–₹20,000 [8]. In addition to the financial burden, frequent voltage fluctuations resulted in repeated motor-winding failures, increasing maintenance costs and causing interruptions in irrigation delivery. Such breakdowns were especially problematic during critical crop-growth periods, when even short delays in water availability could adversely affect agricultural operations. The increasing availability and declining cost of solar photovoltaic (PV) technology provide an opportunity to address these limitations. Solar-powered pumping can reduce dependence on conventional electricity, provide daytime energy for irrigation, lower recurring energy expenditure, and reduce greenhouse-gas emissions. For existing government irrigation infrastructure, solarization is particularly attractive because it offers the possibility of modernizing pumping systems while retaining much of the existing hydraulic infrastructure. The Government of Uttar Pradesh has promoted improved irrigation access and greater energy self-reliance through initiatives associated with "Aatmanirbhar Uttar Pradesh" and "Har Khet Ko Pani" [7]. Within this broader policy framework, the Irrigation and Water Resources Department selected the Hriday Nagar Lift Pump Canal for solarization during 2025–26. The intervention involved integration of the existing pumping arrangement with a 25 kW on-grid solar photovoltaic plant and a 25 kW Variable Frequency Drive (VFD). The approach is also consistent with the national Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM), which promotes solarization of agricultural pumps and associated power infrastructure as a means of improving energy security and supporting sustainable irrigation [12].

Although numerous studies have examined solar irrigation pumps in terms of technical feasibility, economic viability, energy savings, and environmental benefits, relatively fewer studies provide month-by-month operational evidence from an existing government-operated lift irrigation canal after solarization. This distinction is important because actual electricity bills and field operating records can demonstrate whether the expected benefits of solarization are realised under normal working conditions rather than only under theoretical or modelled scenarios. Against this background, the present study evaluates the solarization of the Hriday Nagar Lift Pump Canal as a practical case of integrating renewable energy with existing public irrigation infrastructure. The assessment is based primarily on 11 months of actual post-commissioning electricity billing data, supplemented by technical and operational information. Particular attention is given to changes in electricity expenditure, operational reliability, energy use, carbon emissions, and the broader implications for irrigation management and farmers.

The study also examines the Hriday Nagar experience in relation to published research on solar irrigation and the broader policy objectives of PM-KUSUM. By comparing conditions before and after solarization, it seeks to determine the practical benefits of the intervention and identify the conditions necessary for its replication. The findings are intended to provide field-based evidence for the potential solarization of other suitable lift pump canals in Uttar Pradesh, contributing to more reliable, economical, energy-efficient, and environmentally sustainable irrigation infrastructure. The principal objectives of the study are to (i) assess the technical and operational performance of the solarized lift pumping system; (ii) quantify changes in electricity expenditure and associated financial savings; (iii) estimate the environmental benefits in terms of reduced grid-energy consumption and CO_2 emissions; (iv) examine the implications of solarization for irrigation reliability and farmers; and (v) evaluate the potential for replication of the Hriday Nagar model across other suitable lift irrigation systems in Uttar Pradesh.

2. Review of Literature

Research on solar powered water pumping goes back further than most people expect. As electricity prices climbed and diesel became less attractive on both cost and pollution grounds, researchers started asking whether photovoltaic panels could reasonably replace either option for irrigation pumps. One of the most cited reviews on this subject was written by Chandel, Naik and Chandel in 2015. They went through a large body of earlier work on solar pumping technology and reported that photovoltaic systems typically pay back their installation cost within four to six years when set against ongoing diesel or grid expense [9]. That figure is a useful benchmark for reading the Hriday Nagar savings later in this study, even though this study does not attempt a full payback calculation of its own since capital cost data was not part of the departmental record collected for this site. A year later Sontake and Kalamkar published an equally wide review that looked closely at system sizing, that is how large a solar array needs to be for a given pump and site [10]. Their review explains something that shows up directly in the Hriday Nagar data too. Solar output is not constant across the year. Cloud cover during the monsoon lowers panel output no matter how well a system is sized in the first place, and this is close to the pattern seen in the August result at Hriday Nagar, where the saving dropped to just 4.41 percent because irradiance was weaker and the pump leaned more on grid backup that month.

Motor protection is another theme that comes up again and again in this literature, and it connects directly to why a Variable Frequency Drive was chosen for this project. A VFD lets a motor's speed and power draw adjust smoothly instead of switching on and off at full load, which is gentler on the winding and avoids the stress that used to burn out the Hriday Nagar pump under fluctuating voltage. Bawa, Sunnu and Sarsah reviewed recent work on photovoltaic pumping for drip irrigation and found that variable speed control was one of the main reasons newer systems held up better over time than older fixed speed designs [13]. Read together with the Bureau of Energy Efficiency's own guidance on VFD use in agricultural pumping [6], which recommends variable frequency control specifically to cut down voltage related motor damage, this body of work gives a fairly solid technical reason for the choice made at Nalkoop Khand Balrampur. Beyond the purely technical side, a great deal has been written recently about India's PM-KUSUM scheme itself, since it counts among the largest solar irrigation programmes anywhere in the world. A 2026 report from the Council on Energy, Environment and Water, done together with CSTEP and the International Institute for Sustainable Development, studied the scheme's feeder level solarization component across several states and found that decentralised solar irrigation can already supply power at roughly ₹3 to ₹4 per unit, well under the ₹6 to ₹7 per unit that utilities typically charge for the same supply [11]. This gap is not far off what is seen at Hriday Nagar, where post solar billing settled into a steady ₹6,000 to ₹7,000 band against a pre solar peak of ₹19,200, though it should be said plainly that this study reports billed rupee amounts rather than a per unit tariff, so the two figures are not measuring exactly the same thing.

The same report also noted that feeder level solarization, called Component C-FLS in the scheme's own language, has grown much faster in the last two years than in the scheme's early years, with more than 40 GW of capacity tendered cumulatively by early 2026 [11]. At the same time, coverage in Down To Earth has pointed out that while distributing standalone solar pumps under PM-KUSUM's Component B has gone fairly smoothly, feeder level work under Component C has moved more slowly in many states because of delays in separating feeders and payment lags from distribution companies [14,16]. This is a useful reminder that a technology working well at one canal, as it clearly does at Hriday Nagar, does not automatically mean it will scale up easily everywhere, since a lot depends on administrative steps that have little to do with the solar panels themselves.

One more study is worth mentioning here because it looked not at the hardware at all but at what keeps these systems running well after installation. Miller and colleagues carried out a systematic review of external support arrangements for solar powered water pumping systems across many countries and found that ongoing technical support, more than the panels or the pump, was the strongest predictor of whether a system kept working properly years later [15]. This lines up with something the Hriday Nagar project already did on its own, since operator training was built into the implementation plan as Phase 5, discussed later in Section 5. It suggests the department's instinct to train local operators from the start, rather than treat that step as an afterthought, was well placed even before this review was written. Taken as a whole, the existing research says solar pumping is now a mature and financially sound choice, that VFDs genuinely help protect motors, and that India's national policy machinery is actively pushing this direction forward, though not without administrative friction along the way. What is harder to find in this literature is a plain month by month account of what happened at one specific, fully working canal after the switch was made. Most published work is either laboratory based, simulation based, or written at the scale of an entire state or scheme. This study tries to fill that narrower gap by reporting eleven straight months of real billing data from a single site, which is a smaller and more grounded claim than a national policy study but one that departmental planners can check against their own records.

3. Study Area and Technical Profile

3.1 Geographic and Historical Context

The Hriday Nagar Lift Pump Canal, located at approximately 27.44° N latitude and 82.33° E longitude, is situated on the right bank of the Chakwa drain in Balrampur district, Uttar Pradesh, India. Commissioned in 1968, the system has provided irrigation services to the surrounding agricultural area for more than five decades. The scheme was developed to utilize available surface water through lift irrigation, thereby providing an alternative to excessive dependence on groundwater-based irrigation. Balrampur district lies close to the India–Nepal border and forms part of the Terai region of Uttar Pradesh. The area is characterized by predominantly flat agricultural terrain, fertile soils, and an agrarian economy largely governed by the kharif and rabi cropping seasons. Reliable and timely irrigation is therefore essential for maintaining agricultural productivity, particularly during periods when rainfall is inadequate or unevenly distributed. The Hriday Nagar Lift Pump Canal serves a Culturable Command Area (CCA) of approximately 166 ha. Within this command area, canal-based surface irrigation has played an important role in meeting crop-water requirements and reducing the need for groundwater abstraction. The long operational history of the scheme also makes it representative of several older lift irrigation installations in Uttar Pradesh that continue to perform an important agricultural function but depend on ageing pumping and conventional grid-based energy systems.

The reliability of the pumping system is particularly important because any prolonged interruption caused by electrical faults, motor failure, or maintenance directly affects the timely delivery of irrigation water to the command area. Such interruptions can become critical during important stages of crop development, when delays in irrigation may adversely affect crop growth, productivity, and farm income. These characteristics made Hriday Nagar a suitable site for evaluating the solarization of an existing lift irrigation system. Rather than developing an entirely new solar irrigation facility, the intervention provided an opportunity to examine whether renewable energy could be effectively integrated with established irrigation infrastructure. Its clearly defined 166 ha command area, long operational record, existing grid-connected pumping arrangement, and availability of electricity-consumption and billing records provided a practical basis for comparing conditions before and after solarization. The site therefore offers a useful real-world case for assessing whether solar photovoltaic technology can improve the energy efficiency, operational reliability, economic performance, and environmental sustainability of an ageing public lift irrigation system. The experience gained at Hriday Nagar may also provide practical guidance for identifying and solarizing other technically suitable lift pump canals in Uttar Pradesh.

3.2 Pre-Solarization Technical Specifications

Table 1. ***Pre-Solarization Technical Specifications of the Hriday Nagar Lift Pump Canal.***

Component	Description	Technical Data
Year of Establishment	Original commissioning	1968
Geographic Location	Chakwa Drain (Right Bank)	27.44°N, 82.33°E
Pump Capacity	Installed motor rating	20 HP
Lifting Head	Working height differential	15 m
Discharge Rate	Water discharge capacity	2.5 Cusecs
Culturable Command Area (CCA)	Total irrigated agricultural land	166 Ha
Pre-Solar Energy Source	Electricity supply	100% Conventional Grid

Table 1 presents the baseline technical characteristics of the Hriday Nagar Lift Pump Canal before solarization. The canal operated with a 20 HP pump, a 15-metre lifting head, and a 2.5 cusec discharge capacity, serving approximately 166 hectares of agricultural land. Before the intervention, the pumping system depended entirely on conventional grid electricity.

3.3 Post-Solarization System Specifications

The solarization of the Hriday Nagar Lift Pump Canal was designed to retain the existing hydraulic system while modernizing its energy supply and motor-control arrangement. The existing 20 HP pump, designed for a 15 m lifting head and a discharge capacity of 2.5 cusec, was retained without modification.

Figure 1. Hriday Nagar Lift Pump Canal Solarisation Actual Site View

Thus, the intervention did not require alteration of the pump, delivery system, canal geometry, or other major hydraulic components. The principal modification involved integration of a 25 kW on-grid Solar Photovoltaic (SPV) system with a 25 kW Variable Frequency Drive (VFD). The VFD provides controlled power delivery to the existing motor and enables improved regulation of motor operation. This approach is particularly significant from a practical engineering perspective because the existing irrigation infrastructure could be solarized without replacing the functional pumping and hydraulic components. By limiting the intervention primarily to the energy-generation and motor-control systems, the project reduced the extent of civil and mechanical modifications required at the site. This demonstrates an important advantage of the Hriday Nagar model: existing lift irrigation infrastructure can potentially be converted to solar-assisted operation through targeted retrofitting rather than complete system replacement.

Table 2. ***Post-Solarization System Specifications of the 25 KW On-Grid SPV-VFD Installation.***

Component	Description	Technical Data
SPV System Capacity	Solar Photovoltaic Plant	25 kW (On-Grid)
Solar Panel Rating	High-efficiency modules	590 W per Panel
VFD Unit	Variable Frequency Drive	25 kW Automatic Control
New Energy Source	Post-solarization supply	Solar-assisted supply with grid connectivity
Panel Service Life	Long-term durability	25+ Years
Annual CO_2 Reduction	Environmental saving	Estimated annual CO_2 reduction: ~20 t CO_2/year

Table 2 summarizes the technical configuration introduced after solarization. The upgraded system consists of a 25 kW on-grid solar photovoltaic plant, 590 W solar modules, and a 25 kW Variable Frequency Drive (VFD) for automatic control and motor protection. The system is also expected to provide a service life exceeding 25 years and reduce annual carbon emissions by approximately 20 metric tonnes of CO_2.

4. Pre-Solarization Challenges

4.1 Intermittent Power Supply: Before solarization, the Hriday Nagar Lift Pump Canal depended entirely on conventional grid electricity and was therefore subject to the rural power-supply roster. The timing and duration of electricity availability did not always coincide with actual crop-water requirements, particularly during peak irrigation periods. Consequently, farmers were often unable to irrigate their fields at the required time and, in some cases, had to depend on electricity supplied during night-time hours. The problem was further aggravated by low and fluctuating voltage, especially during periods of high agricultural electricity demand. Unstable voltage affected pump performance, reduced operational reliability, and increased electrical stress on the motor. Repeated voltage fluctuations also contributed to motor-winding failures, maintenance requirements, and interruptions in pumping operations. The impact of unreliable pumping was particularly significant for farmers located toward the tail end of the canal command area, where continuity of discharge is essential for adequate water delivery. Interruptions or reduced pump performance delayed the availability of irrigation water to these fields and made irrigation scheduling difficult. Thus, dependence on an intermittent and voltage-unstable grid supply created a combination of unreliable irrigation scheduling, reduced operational efficiency, increased risk of motor failure, and uncertainty in water delivery, highlighting the need for a more reliable and sustainable energy source for the lift irrigation system.

4.2 Economic Burden: Before solarization, the 20 HP pump depended entirely on grid electricity, resulting in high and variable operating costs. During peak irrigation months, particularly June and July, monthly electricity bills reached approximately ₹19,000–₹20,000. This recurring expenditure placed an additional burden on departmental resources required for maintenance and other irrigation works. Therefore, reducing grid dependence through solarization offered an effective means of lowering electricity costs, stabilizing operational expenditure, and improving the long-term economic sustainability of the system.

4.3 Mechanical Failures: Before solarization, frequent voltage fluctuations and unstable grid supply adversely affected the 20 HP pump motor and its electrical components. Repeated voltage variations increased stress on the motor windings, leading to winding failures and motor burnouts [6]. Faults in the electrical control panel further increased the risk of pump breakdown. Motor failure required rewinding or repair by skilled technicians, resulting in additional maintenance costs and extended periods of pump shutdown. During such breakdowns, irrigation supply to the 166 ha command area was interrupted, creating serious difficulties for farmers, particularly when failures occurred during critical stages of crop growth. Thus, improving voltage stability and motor protection was an important technical requirement of the solarization project.

4.4 Social Impact: Before solarization, unreliable daytime electricity often forced farmers to operate the irrigation system during night-time power availability. This created inconvenience and safety concerns, particularly for farmers travelling to fields through poorly illuminated rural areas. The problem was especially significant for women farmers, for whom night-time irrigation could involve additional safety and mobility challenges. Uncertainty in power availability also made irrigation and crop planning difficult. Farmers could not always be assured of receiving water at critical stages of crop growth, which discouraged the adoption of crops requiring timely and frequent irrigation. Thus, unreliable electricity supply affected not only irrigation convenience but also farmer safety, crop-management flexibility, and overall agricultural productivity.

5. Implementation Methodology

The solarization of the Hriday Nagar Lift Pump Canal was implemented through a systematic five-phase approach comprising site assessment, system design, VFD integration, testing and commissioning, and operator training. The methodology broadly follows the recommended sequence for agricultural SPV-based pumping systems [9,13]. This phased approach ensured that the solar PV capacity was appropriately matched with the existing 20 HP pump, while maintaining operational reliability and long-term system performance.

Table 3. ***Five-Phase Implementation Methodology Followed at the Hriday Nagar Lift Pump Canal.***

Phase	Stage	Details
Phase 1	Site Survey & Load Assessment	Detailed analysis of Chakawa drain's geographic characteristics and precise measurement of the pump's energy consumption profile across seasons.
Phase 2	Design & Capacity Determination	Customised SPV system design for the 20 HP pump, ensuring optimal energy generation-consumption balance across all seasons.
Phase 3	VFD Installation	Deployment of modern Variable Frequency Drive technology-controlled motor operation, speed control, soft starting and motor protection.
Phase 4	Testing & Commissioning	Successful trial of the system was conducted under solar-only conditions during commissioning. Performance benchmarking against design specifications.
Phase 5	Operator Training	Specialized training programme for local pump operators on routine operations, monitoring protocols, and preventive maintenance of the SPV-VFD system.

Table 3 outlines the five-phase implementation methodology adopted for the solarization project. The process progressed systematically from site survey and load assessment to system design, VFD installation, testing and commissioning, and finally operator training. This phased approach ensured appropriate system sizing, reliable operation, motor protection, and long-term maintenance capability.

The first two phases focused on establishing the actual pumping and energy requirements of the site. Proper load assessment and system sizing were essential to avoid both under sizing, which could reduce pumping reliability, and oversizing, which would unnecessarily increase the capital cost of the project. In the third phase, the 25 kW VFD was integrated with the existing pumping system to provide controlled motor operation and protection. This was particularly important because voltage fluctuations and repeated motor-winding failures had been among the major operational problems before solarization. Following installation, the complete system was tested and commissioned under actual operating conditions to verify satisfactory pump performance and compatibility between the solar PV system, VFD, and existing motor. Finally, local operators were trained in system operation, monitoring, troubleshooting, and preventive maintenance to support reliable long-term operation [15]. Overall, the five-phase methodology enabled the existing lift irrigation system to be solarized without major modification of its hydraulic infrastructure, providing a practical retrofit approach that can potentially be adapted to other suitable lift pump canals.

Figure 2. Integrated SPV–VFD Lift Irrigation System at Hriday Nagar: Pump–Motor Assembly, Electrical Control System, and Solar PV Installation at the Canal Site.

6. Results and Performance Analysis

The performance of the solarized Hriday Nagar Lift Pump Canal was evaluated from technical, economic, and irrigation perspectives. The technical assessment examined the theoretical behaviour of the Solar Photovoltaic (SPV)–Variable Frequency Drive (VFD) pumping system using MATLAB-based analysis and pump affinity laws, with particular emphasis on the relationships among operating frequency, power requirement, discharge, and developed head. The economic assessment was based on an eleven-month comparison of electricity bills before and after solarization to quantify cost savings, expenditure variability, and the simple payback period. In addition, the operational impact of solarization was assessed in terms of pumping reliability and irrigation delivery across the 166 ha Culturable Command Area (CCA). The results provide an integrated assessment of the technical performance, economic viability, and irrigation benefits of the SPV–VFD-based lift irrigation system under field operating conditions.

6.1 Theoretical Performance Analysis of the Solar Photovoltaic (SPV)–Variable Frequency Drive (VFD) Pumping System: A MATLAB-based theoretical model was developed to evaluate the performance of the SPV–VFD-driven pumping system at different operating frequencies. The model was based on the rated characteristics of the existing pump: 20 HP (14.92 kW) rated power, 50 Hz rated frequency, 15 m lifting head, and 2.5 cusecs (254.9 m^3/h) rated discharge**.** The technical performance of the solarized pumping system was assessed by examining the theoretical relationship between PV/VFD power supplied to the pump and the corresponding pump discharge. The existing 20 HP (14.92 kW) pump, operating at a 15 m lifting head, has a rated discharge of 2.5 cusecs (approximately 254.9 m^3/h). As shown in Figure 3, the theoretical curve indicates a progressive increase in pump discharge with increasing power supplied through the VFD, reaching the rated discharge at approximately 14.92 kW. This demonstrates the potential of the VFD to regulate pump

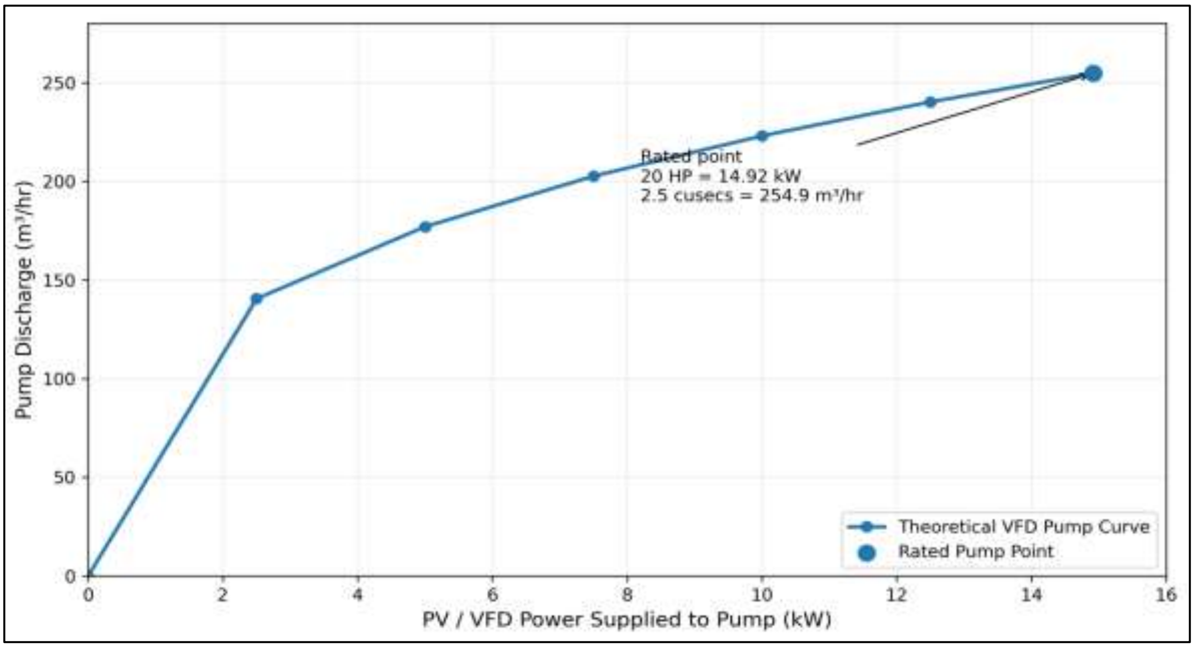

Figure 3. Theoretical Relationship between PV/VFD Power Supply and Pump Discharge for the 20 HP Pump at Hriday Nagar Lift Pump Canal.

operation according to the available solar power while maintaining the required pumping capacity. The intermediate discharge values are theoretical estimates based on pump affinity relationships and should therefore be considered indicative until validated through field measurements. Therefore, the intermediate PV/VFD power–discharge values shown in the curve represent theoretical part-load characteristics, whereas the 14.92 kW–2.5 cusecs point represents the rated operating condition of the installed pumping system.

The pump at the Hriday Nagar Lift Pump Canal is operated at its rated frequency of 50 Hz, corresponding to a rated motor power of 20 HP (14.92 kW) and a discharge capacity of 2.5 cusecs (254.9 m^3/h). The MATLAB analysis at lower frequencies (30–45 Hz) was performed only as a theoretical sensitivity assessment based on pump affinity laws and does not represent the actual operating condition of the installed pump. Under normal operation, the VFD maintains the required 50 Hz supply to the pump when adequate solar power is available, while providing controlled motor operation and electrical protection. Therefore, the lower-frequency power values should be interpreted only as theoretical estimates illustrating the influence of frequency variation on pump characteristics, rather than as measured or routinely used operating conditions at the Hriday Nagar site.

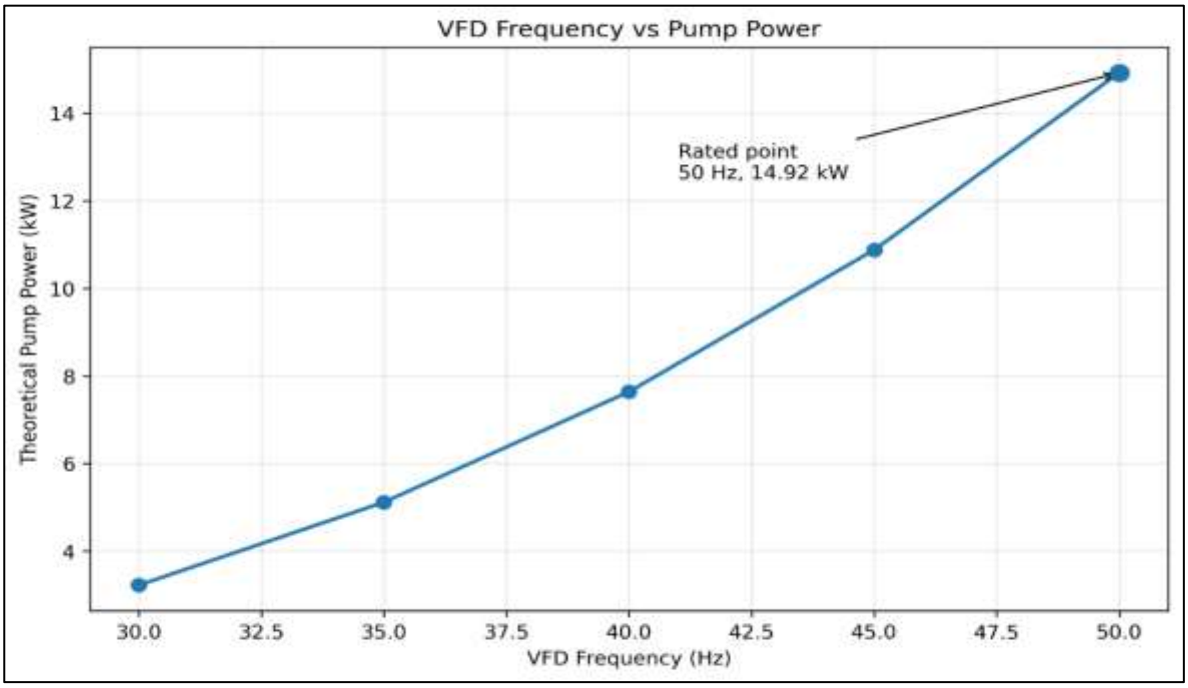

Figure 4. Theoretical VFD Frequency–Pump Power Relationship

The theoretical developed head is strongly influenced by VFD frequency. Based on affinity-law scaling, the corresponding head decreases from 15.0 m at 50 Hz to 12.15 m at 45 Hz, 9.60 m at 40 Hz, 7.35 m at 35 Hz, and 5.40 m at 30 Hz.

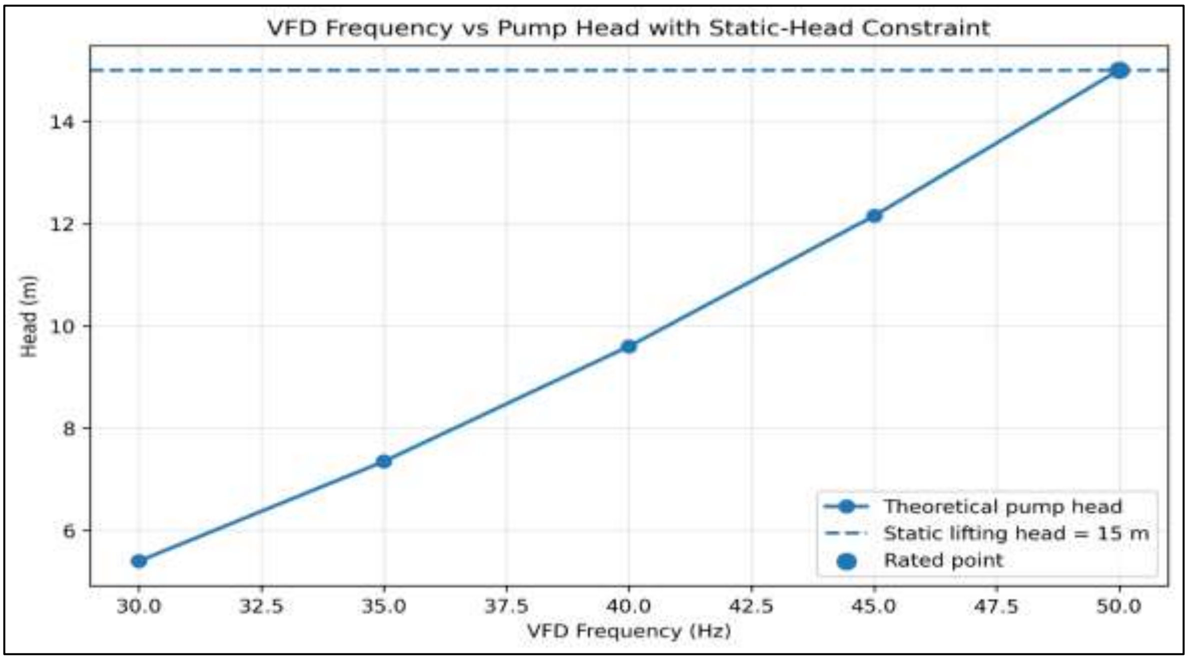

Figure 5. Theoretical VFD Frequency–Head Relationship under the 15 m Rated Lifting-Head Constraint

The Hriday Nagar system has a rated lifting head of 15 m, making the available pump head an important hydraulic constraint. This result shows that energy reduction alone cannot be used to predict successful pumping at reduced VFD frequencies. The pump must first develop sufficient head to overcome the static lift and associated hydraulic losses before useful discharge can occur. Therefore, lower-frequency affinity-law discharge values should be regarded as theoretical trends rather than actual field discharge values.

6.2 Monthly Electricity Bill Comparison (2024 vs. 2025-26)

Table 4. ***Monthly Electricity Bill Comparison Before and After Solarization, May 2024 to March 2026.***

Month	Bill 2024 (₹)	Bill Post-Solar 2025-26 (₹)	Saving (₹)	Saving (%)
May	12,650	6,500	6,150	48.62%
June	19,200	6,200	13,000	67.71%
July	17,100	6,250	10,850	63.45%
August	6,800	6,500	300	4.41%
September	9,000	6,200	2,800	31.11%
October	14,200	6,400	7,800	54.93%
November	9,500	6,500	3,000	31.58%
December	10,400	6,500	3,900	37.50%
January	10,400	7,000	3,400	32.69%
February	10,400	7,000	3,400	32.69%
March	12,850	7,000	5,850	45.53%
TOTAL / AVERAGE	1,32,500	72,050	60,450	~45.6%

Table 4 demonstrates the financial impact of solarization through a month-by-month comparison of electricity bills. Over the eleven-month period, total electricity expenditure declined from ₹1,32,500 to ₹72,050, generating savings of ₹60,450, or approximately 45.6%. The highest monthly saving occurred in June at 67.71%, while post-solarization bills remained relatively stable between ₹6,200 and ₹7,000.

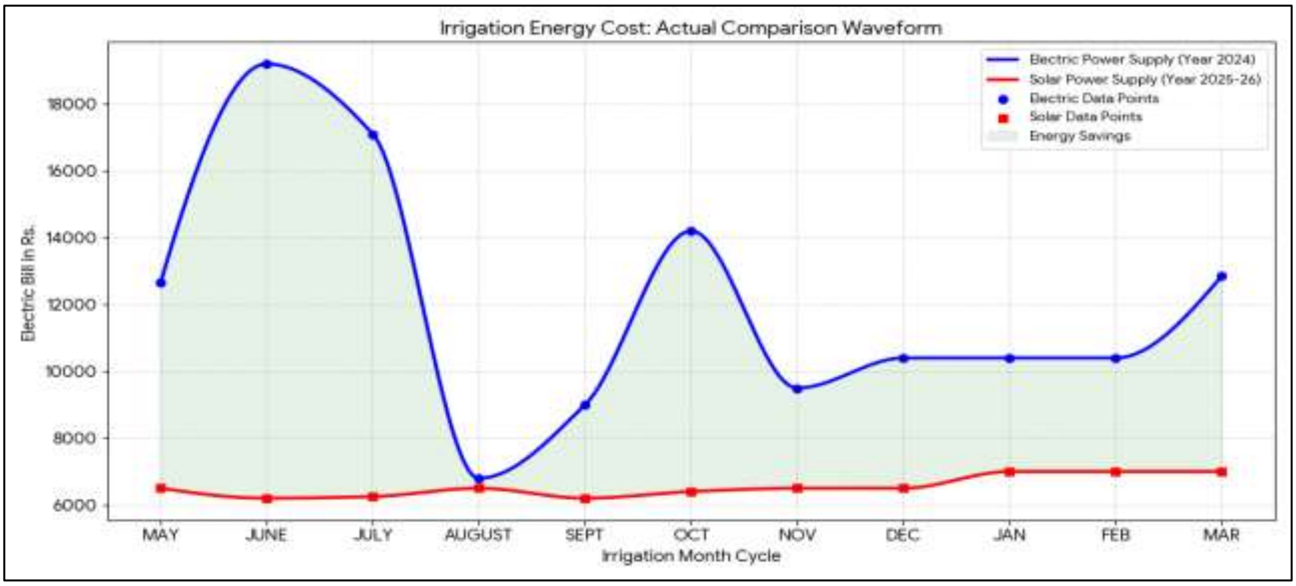

Figure 6. Financial impact of solarization through a month-by-month comparison of electricity bills

6.3 Key Statistical Observations: The post-solarization billing data show a clear reduction in electricity expenditure. The highest saving was recorded in June, when the monthly bill decreased from ₹19,200 to ₹6,200, resulting in a saving of ₹13,000 (67.71%). July also recorded a substantial reduction of 63.45%. Over the 11-month study period, total electricity expenditure decreased from ₹1,32,500 before solarization to ₹72,050 after solarization, generating a total saving of ₹60,450, equivalent to an overall reduction of approximately 45.6%. Another important observation is the stability of post-solarization expenditure, with monthly bills remaining within a narrow range of ₹6,200–₹7,000, compared with the much wider pre-solarization range of ₹6,800–₹19,200. Seasonal variation was also observed. The lowest saving occurred in August (4.41%), which may be attributed to reduced solar generation during the monsoon period and consequently greater dependence on grid electricity. In contrast, higher savings were recorded during May, June, July, and October, when reductions exceeded 45%.

Based on the observed saving of ₹60,450 over 11 months, the annualized electricity saving is approximately ₹65,945. Considering the total installation cost of ₹12.0 lakh and zero annual O&M cost, the simple payback period is approximately 18.2 years. The actual long-term economic benefit may be higher if future electricity tariff escalation and savings from reduced motor failures and maintenance are also considered. Overall, the results demonstrate that solarization achieved both substantial electricity-cost reduction and greater stability in monthly operating expenditure, while the seasonal pattern confirms the importance of retaining grid connectivity during periods of lower solar availability.

6.4 Payback Period: Based on a total installation cost of ₹12.0 lakh, no separate annual O&M expenditure was included in the available project-cost data., and the observed saving of ₹60,450 over 11 months, the annualized electricity saving is approximately ₹65,945. Therefore, the simple payback period is approximately 18.2 years. This estimate is conservative, as it excludes future electricity tariff escalation and additional financial benefits arising from reduced motor failures, maintenance costs, and irrigation downtime.

6.5 Irrigation Coverage of the Culturable Command Area (CCA): The Hriday Nagar Lift Pump Canal provides irrigation to a 166 ha Culturable Command Area (CCA). Following solarisation, improved daytime pumping and operational reliability have strengthened timely and continuous water delivery across the command area, including tail-end fields. This has improved irrigation reliability and reduced the risk of inadequate water supply to farmers located at the tail end of the canal system.

Figure 7. Irrigation Water Distribution in the Hriday Nagar Command Area

Reliable pumping has also improved the continuity of canal discharge, which is particularly important for effective tail-end feeding. Farmers can receive irrigation water more predictably during critical crop-growth periods, reducing uncertainty in irrigation scheduling. Improved surface-water availability can also reduce dependence on private borewells and tubewells. Overall, solarization has strengthened the equitable, reliable, and sustainable delivery of irrigation water from the head to the tail end of the command area.

7. Environmental Impact Assessment

7.1 Carbon Emission Reduction: The transition from conventional grid electricity to on-grid solar photovoltaic power results in a verified annual reduction of approximately 20 metric tonnes of CO_2 emissions. This calculation is based on the standard grid emission factor for Uttar Pradesh's electricity supply mix [2] and the annual energy generation capacity of the 25 KW SPV system. Twenty metric tonnes is not a figure that means much on its own unless it is placed next to something familiar. The United States Environmental Protection Agency estimates that a typical passenger car emits about 4.6 metric tonnes of CO_2 a year [18], so the saving from this one 25 KW installation works out to roughly the same as taking four passenger cars off the road for a full year, every year, for as long as the system keeps running. Scaled up across even a modest share of Uttar Pradesh's lift pump canal network, a saving of this size per site stops looking like a rounding error and starts looking like a real contribution to the state's emission profile.

Annual avoided CO_2 (kg/year) = Solar electricity utilized (kWh/year) × Grid emission factor (kg CO_2/kWh)

For the present study, the grid emission factor was taken as 0.716 kg CO_2/kWh, based on the average CO_2 emission factor of Indian grid electricity reported by the Central Electricity Authority (CEA).

For an estimated annual solar electricity utilisation of approximately 28,000 kWh/year:

Annual avoided CO_2 = 28,000 × 0.716

= 20,048 kg CO_2/year

Since,

1 metric tonne = 1,000 kg

Therefore,

Annual avoided CO_2 = 20,048 / 1,000

= 20.05 metric tonnes CO_2/year

Thus, the 25 kW SPV system is estimated to avoid approximately 20 metric tonnes of CO_2 emissions annually. Over a 25-year service life, assuming similar annual solar utilization and without accounting for PV degradation or future changes in the grid emission factor, the cumulative avoided emissions would be approximately:

20.05 × 25 = 501.25 metric tonnes of CO_2

Therefore, the solarization of the Hriday Nagar Lift Pump Canal provides a measurable environmental benefit in addition to reducing grid electricity consumption and operating expenditure. Replication of similar SPV systems across lift irrigation schemes could contribute to reducing the carbon footprint of the irrigation sector

7.2 Groundwater Conservation: Reliable operation of the Hriday Nagar Lift Pump Canal has strengthened the availability of surface-water irrigation within its 166-ha command area. When canal water is available at the required time, farmers have less need to depend on private bore wells and tube wells as alternative irrigation sources. Reduced dependence on groundwater can help lower groundwater abstraction pressure and support long-term aquifer sustainability. This represents an important indirect environmental benefit of reliable solar-powered canal irrigation, particularly in areas where groundwater resources are increasingly used for agricultural purposes. However, long-term monitoring of groundwater levels would be required to quantify the actual impact of the project on the local water table. Therefore, the present study identifies reduced pressure on groundwater extraction as a potential co-benefit, rather than attributing measurable groundwater-level recovery solely to solarization.

7.3 Ecological Co-Benefits: In addition to reducing grid-related carbon emissions, the solarization of the Hriday Nagar Lift Pump Canal provides several ecological co-benefits. Solar PV generation operates without direct fuel combustion, resulting in negligible operational air pollution and low noise levels compared with conventional diesel-based backup power. The system also reduces dependence on fossil-fuel-based energy sources and their associated requirements for fuel transportation, storage, and periodic servicing. With an expected service life of more than 25 years, the solar PV installation offers the potential for sustained environmental benefits over the long term. Overall, the transition toward solar-based pumping contributes to a cleaner, quieter, and more sustainable irrigation system, complementing the estimated reduction of approximately 20 metric tonnes of CO_2 emissions per year.

8. Social Impact and Farmer Empowerment

8.1 Stability in Irrigation Scheduling: Solar-powered irrigation guarantees daytime water availability from sunrise to sunset, independent of erratic grid supply schedules. Farmers across the 166-hectare command area can now plan their irrigation cycles in advance with full confidence, enabling more efficient water use and crop management, a pattern consistent with the daytime-supply benefits reported for PM-KUSUM feeder-solarized sites elsewhere in India [11,14].

8.2 Crop Diversification: Reliable and timely irrigation can create favourable conditions for crop diversification within the Hriday Nagar command area. Under the earlier grid-dependent system, uncertainty in water availability encouraged farmers to rely mainly on traditional crops such as paddy and wheat, which are relatively familiar and established within the local farming system. Following solarization, improved daytime availability and predictability of irrigation water provide farmers with greater flexibility to consider vegetables, cash crops, and other higher-value crops that require more timely and controlled irrigation. Such diversification has the potential to improve land productivity and farm income, provided that suitable market access, crop selection, and agricultural support are available. Thus, solarization can contribute not only to reliable irrigation but also to creating conditions for more diversified and economically productive agriculture. However, long-term crop-area and farm-income data would be required to quantify this impact.

8.3 Empowerment of Women Farmers: One of the important social benefits of solarization is the improved availability of daytime irrigation. Under the earlier grid-dependent system, irregular power schedules sometimes required farmers to access their fields at night, creating safety and mobility concerns, particularly for women farmers. Improved daytime water availability reduces the need for night-time irrigation and allows agricultural activities to be carried out during safer and more convenient hours. This can improve safety, accessibility, and participation of women in irrigation-related activities, while also reducing the inconvenience associated with uncertain power schedules. Although these benefits were observed through departmental field experience, no formal socio-economic survey of women farmers was conducted. Therefore, the findings should be interpreted as an important qualitative social benefit of the project rather than a quantitatively measured impact.

8.4 Energy Literacy and Community Awareness: The installation of a solar-powered irrigation system has also created opportunities for improving energy awareness among local farmers and pump operators. Regular interaction with the SPV–VFD system provides practical exposure to solar-energy generation, system operation, monitoring, and basic maintenance. Operator training further strengthens local technical capability and can support the early identification of operational problems and improved routine maintenance, which is important for the long-term sustainability of solar pumping systems [15]. The project also serves as a practical demonstration of renewable-energy technology within the local community and may encourage greater awareness and acceptance of solar energy. However, as community energy literacy was not formally assessed through a structured survey, these outcomes should be considered qualitative co-benefits rather than quantitatively established impacts.

8.5 Digital Monitoring and Data Management

The solarized system incorporates digital monitoring of energy generation and operational performance, enabling the department to track system behaviour and identify abnormalities at an early stage. Such monitoring supports a shift from breakdown-based maintenance toward preventive and data-driven maintenance, thereby improving operational reliability and reducing avoidable downtime. Digital records also improve transparency, accountability, and performance evaluation by providing reliable operational data for departmental review and future technical assessment. When combined with electricity billing records, these data provide a stronger basis for evaluating energy savings, system efficiency, and long-term performance. Thus, digital monitoring strengthens the Hriday Nagar project beyond solar power generation by supporting evidence-based operation, maintenance, and management of the lift irrigation system.

9. Comparative Analysis: Pre and Post Solarization

Table 5 summarizes the key changes in the Hriday Nagar Lift Pump Canal before and after solarization. The comparison highlights improvements in energy use, electricity cost, pumping reliability, environmental performance, and irrigation service. It provides an overall assessment of the benefits achieved through the integration of the SPV–VFD system with the existing pumping infrastructure.

Table 5. ***Side-by-Side Comparison of the Legacy Grid-Powered System and the Post-Solarization SPV-VFD System.***

Parameter	Legacy System (Pre-Solar)	Solar System (Post-Solarization)
Energy Source	100% conventional grid electricity	Solar-assisted electricity supply with grid connectivity
Operational Cost	High electricity bills, ₹19,000+ at peak	₹6,000-7,000 stable, 45.6% overall saving; maximum monthly saving 67.71%.
Irrigation Availability	Uncertain due to power rosters and tripping	Sunrise to sunset guaranteed supply
Technical Reliability	Motor burnout risk from voltage fluctuations	VFD provides controlled motor operation and protection
Environmental Impact	Significant carbon footprint from grid power	~20 T CO_2 reduction per annum
Farmer Welfare	Forced nocturnal irrigation, safety concerns	Reduced need for night-time irrigation and improved daytime accessibility
Women Farmers	Night-time dependence, unsafe conditions	Independent, safe daytime access

Table 5 provides an overall comparison between the legacy grid-powered system and the post-solarization SPV-VFD system. The findings indicate improvements not only in electricity cost but also in irrigation reliability, motor protection, environmental performance, farmer safety and women's daytime access to fields. Thus, solarization produced combined economic, technical, environmental, and social benefits for the Hriday Nagar command area.

10. Scalability and Replication Potential

The Hriday Nagar project demonstrates that solar PV and VFD technology can be successfully integrated with an existing lift irrigation system without major modification of its hydraulic infrastructure. This retrofit-based approach provides significant potential for replication across other suitable lift pump canals in Uttar Pradesh, particularly those experiencing high electricity expenditure, unreliable grid supply, and recurring motor-related problems. A major advantage of the model is its adaptability to different pump capacities. The basic approach—assessment of pump load, appropriate sizing of the SPV system, integration of VFD control, testing, and operator training—can be applied to other installations after suitable site-specific assessment. However, solar capacity should not be replicated directly from Hriday Nagar, as each site may differ in pump capacity, lifting head, discharge, operating hours, solar availability, and irrigation demand. Large-scale adoption could reduce the Irrigation and Water Resources Department's dependence on conventional grid electricity, stabilize recurring energy expenditure, improve pumping reliability, and contribute to reductions in carbon emissions. The approach is also broadly consistent with India's policy direction toward the solarization of agricultural energy systems under PM-KUSUM [11]. However, replication should be based on technical and economic feasibility assessment for each site. Priority may be given to lift irrigation systems with high annual electricity consumption, adequate solar exposure, suitable land availability, ageing electrical control systems, and significant irrigation demand. Financial viability should also consider installation cost, expected electricity savings, equipment life, applicable subsidies, and avoided maintenance costs. Therefore, the Hriday Nagar model provides a practical framework for the phased solarization of suitable lift irrigation infrastructure in Uttar Pradesh. A systematic state-wide assessment followed by site-specific design and performance monitoring could enable its effective expansion while ensuring that future installations remain technically appropriate and economically justified.

11. Discussion

The Hriday Nagar Lift Pump Canal demonstrates that integrating solar PV with an existing lift irrigation system can substantially reduce dependence on grid electricity. The maximum monthly saving reached 67.71% in June, while the overall electricity-cost reduction during the 11-month study period was approximately 45.6%, broadly supporting earlier findings on the economic benefits of solar irrigation pumping [9,10]. Post-solarization electricity bills remained relatively stable at ₹6,200–₹7,000 per month, compared with the wider pre-solarization range of ₹6,800–₹19,200. The lower saving observed in August (4.41%) is consistent with reduced solar generation during monsoon conditions [9], highlighting the advantage of retaining grid connectivity during periods of low solar availability. The 25 kW VFD provides controlled motor operation and protection, addressing the voltage-related operational problems associated with the earlier system [6,13]. Operator training further supports reliable long-term operation, consistent with studies emphasizing the importance of local technical capacity for sustainable solar irrigation systems [15]. Based on an installation cost of ₹12.0 lakh and annualized electricity savings of approximately ₹65,945, the simple payback period is about 18.2 years. However, this estimate excludes future electricity tariff escalation and potential savings from reduced maintenance and motor failures. Overall, the results support the objectives of PM-KUSUM [11,14] and demonstrate the potential of solar PV–VFD retrofitting for existing lift irrigation infrastructure. However, as this is a single-site case study, replication should be based on site-specific technical and economic assessment.

12. Conclusions

The solarization of the Hriday Nagar Lift Pump Canal, Balrampur, demonstrates the practical potential of integrating renewable energy with existing lift irrigation infrastructure. The installation of a 25 kW on-grid SPV system with a 25 kW VFD, while retaining the existing 20 HP pump, reduced dependence on grid electricity and field experience indicates improved operational reliability of irrigation service to the 166 ha command area. Based on 11 months of actual billing data, electricity expenditure decreased by approximately 45.6% overall, with the maximum monthly reduction of 67.71% in June. Post-solarization bills remained relatively stable at ₹6,200–₹7,000 per month, compared with a pre-solarization peak of ₹19,200. The system is also estimated to avoid approximately 20 metric tonnes of CO_2 emissions annually. With an installation cost of ₹12 lakh and annualized electricity savings of approximately ₹65,945, the simple payback period is estimated at 18.2 years, excluding future tariff escalation and potential savings from reduced maintenance and motor failures. The significance of the Hriday Nagar case lies in its use of actual operational and billing data rather than projected benefits. While the results from a single site should not be generalized to every lift irrigation scheme, they demonstrate that appropriately designed SPV–VFD retrofitting can provide measurable energy, economic, operational, and environmental benefits. The model therefore offers a practical basis for phased replication across other suitable lift pump canals in Uttar Pradesh, subject to site-specific technical and economic feasibility assessment.

Acknowledgements

The authors gratefully acknowledge the far-sighted vision and visionary leadership of the Hon'ble Chief Minister of Uttar Pradesh, Shri Yogi Adityanath Ji, whose commitment to sustainable development, modernization of irrigation infrastructure, and farmer welfare provided the guiding impetus for this initiative. The authors also express their sincere gratitude to the Hon'ble Jal Shakti Minister, Shri Swatantra Dev Singh Ji, whose practical and result-oriented approach transformed this vision into action on the ground, facilitating the effective implementation of the project. Special appreciation is also extended to the farmers of the Hriday Nagar Lift Pump Canal command area for their valuable cooperation, active participation, and constructive feedback throughout the implementation process. Their support played an important role in translating this initiative into a practical model of sustainable, energy-efficient, and farmer-oriented irrigation management.

References

[1] Bawa, A.-R., Sunnu, A. K., & Sarsah, E. A. (2023). Recent advances in solar-powered photovoltaic pumping systems for drip irrigation. *iRASD Journal of Energy & Environment, 4*(2). https://doi.org/10.52131/jee.2023.0402.0040

[2] Bureau of Energy Efficiency. (2023). *Guidelines for variable frequency drive (VFD) application in agricultural pumping systems*. Government of India.

[3] Central Electricity Authority. (2024). *CO_2 baseline database for the Indian power sector* (Version 17). Government of India.

[4] Chandel, S. S., Naik, M. N., & Chandel, R. (2015). Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies. *Renewable and Sustainable Energy Reviews, 49*, 1084–1099. https://doi.org/10.1016/j.rser.2015.04.083

[5] Down To Earth. (2026). *PM-KUSUM: Why India's solar irrigation scheme needs stronger institutions for energy and water security*. https://www.downtoearth.org.in

[6] India Brand Equity Foundation. (2026). *PM-KUSUM Yojana, solar energy scheme: Scheme components and financial assistance structure*. https://www.ibef.org

[7] International Renewable Energy Agency. (2023). *Renewable power generation costs in 2023*. International Renewable Energy Agency.

[8] Irrigation and Water Resources Department. (2025). *Hriday Nagar lift pump canal solarization: Project report*. Nalkoop Khand, Balrampur, Uttar Pradesh.

[9] Miller, M., Appling, C., Ellis, N., & Bartram, J. (2024). External support for solar-powered water pumping systems in rural areas: A systematic review. *Environmental Science & Technology, 58*(41), 18053–18063. https://doi.org/10.1021/acs.est.4c01264

[10] Ministry of New and Renewable Energy. (2024). *Annual report 2023–24: Solar energy programme*. Government of India.

[11] Ministry of New and Renewable Energy. (2026). *Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyaan (PM-KUSUM): Scheme overview*. https://www.mnre.gov.in

[12] National Solar Energy Federation of India. (2024). *Best practices in agricultural solarization*. NSEFI.

[13] Rahman, A., Tunga, A., Chandra, H., Dutta, P., Sharma, B., Mallik, E. V., Bandopadhyay, R., Jha, A. K., Garg, R., & Agarwal, D. (2026). *Scaling solar power for irrigation in India: Lessons from PM-KUSUM*. Council on Energy, Environment and Water, CSTEP, and International Institute for Sustainable Development.

[14] Saurenergy. (2026). *PM-KUSUM's missing link: Why India's solar pump success isn't yet an agricultural energy revolution*. https://www.saurenergy.com

[15] Singh, S. K., & Achyutanand. (2025). *Field performance data: Hriday Nagar lift pump canal, Balrampur: Monthly electricity bill analysis 2024–2026* [Unpublished departmental data]. Nalkoop Khand, Balrampur.

[16] Sontake, V. C., & Kalamkar, V. R. (2016). Solar photovoltaic water pumping system: A comprehensive review. *Renewable and Sustainable Energy Reviews, 59*, 1038–1067. https://doi.org/10.1016/j.rser.2016.01.021

[17] State Planning Commission, Uttar Pradesh. (2025). *Vision document: Aatmanirbhar Uttar Pradesh: Energy self-reliance in agriculture*. Government of Uttar Pradesh.

[18] United States Environmental Protection Agency. (2024). *Greenhouse gas emissions from a typical passenger vehicle*. https://www.epa.gov/greenvehicles