Sustainable Green Irrigation: A Comparative Economic and Environment Analysis of Solar VS Micro-Hydroelectric Tube Wells

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Abstract

Escalating fuel prices significantly impact irrigation costs, prompting scholars to seek sustainable solutions. This study compares two green irrigation systems for rural Pakistan: micro-hydroelectric and solar tube wells. Data from farmers, agroengineering experts, and INCPAK were analyzed for economic and environmental impacts. The findings show that micro-hydroelectric tube wells outperform solar tube wells in net present value (NPV), internal rate of return (IRR), payback period (PP), and benefit-cost ratio (BRC). Both systems are environmentally friendly, emitting no CO2, but micro-hydroelectric wells have a greater positive impact on reducing greenhouse gas (GHG) and air pollution emissions (APE). While solar technology is a viable alternative, sun exposure limits its efficiency. The study concludes that micro-hydroelectric tube wells are a more sustainable and preferable option for rural areas with limited energy access and high fuel costs. This research supports policymakers in promoting eco-friendly irrigation technologies and suggests future studies on funding, market introduction, and impacts on productivity and welfare.

Keywords: Sustainable Green Irrigation, Economic Analysis, Environment Analysis, Renewable and Eco-friendly Tube-wells.

Introduction

The rising costs of diesel and electricity have made traditional tube wells for irrigation increasingly unsustainable, particularly due to soaring fuel prices, electricity tariffs, and growing environmental concerns. These escalating expenses have made groundwater-dependent irrigation methods financially unviable for many farmers, who now face the burden of exorbitant fuel costs (Razzaq et al., 2023). Agriculture requires continuous investment in specific inputs such as fertilizers, herbicides, and water (Qamar et al., 218). Among these, water is the most frequently needed, with crops generally requiring irrigation 5 to 8 times per season. Consequently, water plays a crucial role in agricultural activities. However, the conveyance efficiency of irrigation systems is often

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inadequate, leading to significant water loss in channels (Mekonnen et al., 2018). The Pakistani government is prioritizing water conservation as a strategy to reduce wastage (Ishfaq et al., 2022). To address limited surface water availability, nearly 4 million tube wells have been constructed to tap into underground water sources for irrigation. Of these, 82% are powered by diesel, while the remaining are electric (Razzaq et al., 2023).

The expansion of electric tube wells has been hindered in recent years due to inadequate energy supply and rising voltage costs. Traditional irrigation methods are becoming increasingly expensive (Xiarchos & Vick, 2011). The widespread use of diesel-powered irrigation systems has also contributed to environmental pollution. Moreover, extending electricity to remote areas is challenging due to insufficient infrastructure and transmission inefficiencies. Building a national grid infrastructure in these isolated areas presents a considerable obstacle (Shabbir et al., 2020). As a result, neither diesel pumps nor electric tube wells are economically feasible options.

The adoption of renewable energy sources, such as wind, solar, biomass, and hydropower, has significantly increased in both the industrial and agricultural sectors as a cost-effective alternative to traditional fuels and electricity (Sadiqa et al., 2021). These renewable sources can reduce production costs and minimize environmental impacts (Sharma et al., 2012). Pakistan, located in the solar belt, benefits from ample sunlight throughout the year. However, to fully harness this potential, substantial investment from both the public and private sectors is required (Ayaz et al., 2020). Solar water pumping systems operate autonomously, eliminating the need for fuel (Foster et al., 2017). Increased use of solar energy can lead to lower power generation costs, reduced greenhouse gas emissions, and help bridge the gap between costs and tariffs (Shabbir et al., 2020). Solar tube wells offer an economically viable and durable alternative for farmers seeking cost-effective irrigation solutions. Regular irrigation boosts agricultural productivity, enhancing food self-sufficiency and export potential.

Multiple studies have shown that solar tube wells are a more advantageous alternative compared to diesel or electric tube wells. For example, Bakhsh et al. (2015), Sadiqa et al. (2021), and Bukhari et al. (2023) demonstrated that solar tube wells offer superior benefits in terms of net present value, payback period, internal rate of return (IRR), and cost-benefit analysis. They suggest that solar tube wells provide greater reliability and cost-effectiveness for irrigation compared to diesel and electric tube wells. However, solar technology is limited by temporal constraints, which can reduce its effectiveness. For instance, Vourvoulias (2023) emphasized that solar energy is affected by both intermittency and variability in sunshine. Glover (2021) criticized the use of rare and precious metals in the production of solar panels, which have a limited lifespan and require regular maintenance. Therefore, the installation and operation of solar-powered tube wells for irrigation can be costly.

Moreover, the effectiveness of solar technology is dependent on sunlight exposure, limiting its operational time to 7-8 hours per day. Due to this limitation, solar technology may not always be sustainable. In contrast, a micro-hydroelectric tube well is not constrained by sunlight and can provide a continuous water supply for nearly 24 hours a day. According to Gorkhali and Prasad (2005), tube wells equipped with micro-hydroelectric technology can irrigate larger areas of land. A micro-hydro system refers to a small-scale hydroelectric power plant that harnesses the energy of flowing water to generate electricity. The turbine, designed specifically for tube wells and bore wells, can directly power mechanical devices and generate electricity for various uses, including residential and agricultural applications. The water expelled from the tube well rotates the turbine (Arun et al., 2016). As the turbine rotates, it generates an electric current, which is then converted from direct current (DC) to alternating current (AC) using an inverter. Thus, a micro-hydroelectric tube well has the potential to significantly reduce irrigation costs and eliminate the emission of harmful gases or substances. There has been limited comparison of renewable and eco-friendly irrigation options in the existing literature, especially between diesel and electric tube wells. Therefore, this study aims to compare the economic and environmental impacts of solar and micro-hydropower tube wells and determine which renewable energy technology is more sustainable for irrigation systems.

This research contributes to the knowledge of renewable energy sources and sustainable irrigation systems by examining alternative energy options. Based on the findings, this study suggests that financial policymakers should fund more sustainable, eco-friendly power technologies for irrigation to save on fuel costs and reduce greenhouse gas emissions. The government can use this study to develop a financial mechanism that helps farmers install sustainable irrigation tube wells. The study's findings can assist in evaluating investments in sustainable irrigation systems. Government financing of micro-hydroelectric tube wells will maximize agricultural productivity while reducing greenhouse gas emissions. Farmers using micro-hydroelectric tube wells will benefit from improved well-being for both themselves and consumers.

Literature Review

This section critically reviews the literature on renewable and sustainable energy irrigation systems, highlighting recent advances and suggesting areas for further research. Modern irrigation techniques and drought-resistant crops have been shown to mitigate water scarcity, a topic that has been extensively studied in agriculture. Qamar et al. (2018) found that water scarcity has increased irrigation costs, negatively impacting farmers' incomes and food security. Their report recommended the adoption of water-efficient technologies, drought-tolerant crops, modern irrigation methods, and better water management practices to address these challenges.

Water loss due to wastage, evaporation, and poor management significantly reduces the effectiveness of irrigation systems (Ahmad & Salam, 2018). Gandhi et al. (2020) noted that inadequate irrigation infrastructure hampers agricultural productivity and profitability in developing countries. Blockages in multiple reservoirs have reduced water storage capacity, leaving farmers with insufficient resources. Additionally, the salinity of river water and the presence of toxic heavy metals have led to decreased crop yields and soil degradation. Khan et al. (2021) recently revealed that water-efficient crops can alleviate water constraints in agriculture. In regions where canals are used for irrigation, water loss can exceed 50% of the total supply (Janjua et al., 2021).

Mekhilef et al. (2013) found that solar energy outperforms traditional energy sources in several ways, including lower noise, pollution, maintenance, and fuel consumption. They highlighted the low operating costs of solar water pumps and recommended assessing photovoltaic solar systems while encouraging government support for more affordable and sustainable energy sources. A 4.48-kilowatt (kW) direct current (DC) solar photovoltaic water pump can potentially conserve approximately 7 to 8 megawatt-hours (MWh) of energy and reduce carbon dioxide ($CO2$) emissions by about 1.2 to 1.4 metric tonnes by minimizing the use of fuel for electricity generation. PV water pump systems could reduce power load shedding for farmers and help revive Pakistan's agriculture industry.

Bakhsh et al. (2015) conducted an economic comparison of diesel-powered and solar tube wells, finding that the solar-powered tube well has a payback period of 2.2 years, making it a viable alternative. Due to its high return on investment (ROI), solar-powered irrigation is both environmentally sustainable and economically viable for farmers. Mustafa et al. (2022) noted that using solar energy for irrigation can reduce water wastage and enhance water efficiency. Renewable energy for irrigation can boost farmers' income, the rural economy, and overall quality of life. Ahmad et al. (2022) explored the potential of wind energy to power agricultural irrigation systems, concluding that wind energy could be a reliable and cost-effective solution in areas with strong wind resources. Bukhari et al. (2023) recently confirmed the findings of Bakhsh et al. (2015), showing that solar-powered tube wells are cost-effective, with an ROI within two years, and are environmentally friendly due to their lack of harmful emissions and noise.

Contemporary literature advocates replacing non-renewable tube wells with renewable alternatives, though solar energy, despite being promising, has limitations. Vourvoulias (2023) pointed out that solar energy is intermittent and variable, and that solar panels require expensive materials like silicon, cadmium, and indium, which have significant environmental impacts during extraction and processing. Solar energy systems are also costly, with solar panels having a lifespan of 20–30 years and requiring frequent maintenance. In contrast, self-generated micro-hydroelectric tube wells offer an alternative to solar-powered systems. This technology generates electricity from the gravitational potential energy of falling water, powering tube wells, lighting, and other agricultural equipment. Farmers benefit from micro-hydroelectric tube well technologies by reducing their reliance on diesel generators, characterized by high energy efficiency and low operational costs.

Tube wells are widely used for agricultural irrigation due to reservoir degradation and river water scarcity. However, this technology requires a significant amount of energy, which is challenging for developing nations like Pakistan, where fuel and electricity costs are rising. Additionally, some countries face electricity shortages, making large-scale diesel and electric tube well operation impractical. Prior studies comparing solar and diesel/electric tube wells have shown that solar-powered systems are more practical. However, solar tube wells are limited by their dependence on sunlight during the day. Therefore, innovative technologies that surpass solar power in sustainability are needed. Given the limited literature comparing renewable and eco-friendly tube well technologies, further comparative studies are required to determine which technology is more sustainable and practical for irrigation systems.

Methodology

Data and Variables

This quantitative study was conducted in Lahore, Pakistan, from November 1, 2022, to February 28, 2023. We collected data by interviewing farmers, suppliers, and solar panel engineering firms. Our data collection methodology was informed by previous studies (e.g., Schmitter et al., 2018; Guno & Augton, 2022; Asad et al., 2022). Specifically, we interviewed farmers to gather information on the annual operating and maintenance costs of tube wells, the water requirements for crops (measured in hours per hectare per season), and the amount of diesel consumed annually to irrigate one hectare of agricultural land. Data on the installation costs of solar tube well systems were obtained from suppliers and engineering firms. To this end, we contacted a solar engineering firm.

The study by Agaton et al. (2020) in the Philippines served as a reference for calculating greenhouse gas emission factors and assessing the economic value of investments, including financial gains, ROI duration, and comparisons of cash inflows and outflows to their present values, based on the collected data. Fuel price data for Pakistan was sourced from online databases such as INCPAK.

In line with prior research conducted by Mustafa et al. (2022) and Asad et al. (2022), we employed economic and environmental analytical tools similar to those used by Agaton and Goron (2022) and Baksh et al. (2016) for our sustainability study. These evaluations provided insights into the financial viability, environmental impact, and sustainability of various energy sources.

Economic Analysis

We utilized the methodology from Agaton et al. (2020) for our economic study, which involved assessing financial indicators such as return on investment (ROI), payback period (PBP), net present value (NPV), and internal rate of return (IRR). This analysis aimed to evaluate the financial viability of solar-powered tube wells compared to conventional tube wells. Additionally, we conducted a comparative economic analysis of solar tube wells and micro-hydroelectric tube wells.

Initial Investment Costs

We employed the methodologies from Mustafa et al. (2022) and Bukhari et al. (2023) to determine the initial installation costs for solar panel tube wells and micro-hydroelectric tube wells. For solar tube wells, primary expenses include the motor, solar panels, controller or inverter, wiring, belt, labor charges, and frame. For micro-hydroelectric tube wells, costs cover the motor, turbine, router, water tank, and labor fees. The costs presented were obtained from suppliers and solar engineering firms specializing in solar irrigation systems.

Costs Associated with Operations of Tube Well

The operating expenses (OC) for both systems include variables such as the operator's salary, maintenance costs, repair expenses, and other recurring expenditures. The formula for calculating operating costs (OC) is the sum of the operator's wage and the maintenance and repair expenses (R&M) incurred annually. These OC statistics are sourced from agro-engineers specializing in hydro and solar projects. Consistent with the findings of Bakhsh et al. (2015), we also assumed that the operational costs of tube wells remain constant.

Cost-Advantage Analysis

This approach involves evaluating the expenses and benefits associated with a specific economic endeavor. The Benefit-Cost Ratio (BCR) measures the relationship between the present value of benefits and the present value of costs. Following the methodology employed by Baksh et al. (2016) and Asad et al. (2022), we used the following model to calculate BCR:

$$BCR = \frac{\sum \frac{B_t}{(1+r)^t}}{\sum \frac{C_t}{(1+r)^t}}$$

Where B_t represents the annual benefits, C_t represents the annual costs, r is the discount rate, and t is the time. Benefits are quantified based on the annual reduction in fuel consumption due to the operation of solar and micro-hydroelectric tube wells. The annual fuel cost savings are used as an indicator of the advantages gained from utilizing renewable energy technologies (Bakhsh et al., 2015; Agaton & Guno, 2022).

Return on Investment

The Return on Investment (ROI) is a numerical metric used to assess the efficiency of both operational and capital investments, enabling comparisons between different investment opportunities (Wu & Buyya, 2015). ROI measures the profitability of an investment as a percentage of the initial cost. The formula for calculating ROI is:

$$ROI = \frac{\sum_{t=1}^{T} R_t - I}{I}$$

In this formula, R_t represents the annual savings, t denotes the evaluation period, and T is the operational lifespan of the solar photovoltaic (PV) systems. The initial capital expenditure is represented by I, which includes both the cost of acquiring the equipment and any additional installation charges. The water needed for irrigating a one-acre farm is estimated based on the combined output of the Guno and Agaton systems (Guno & Agaton, 2022). Factors influencing both systems equally include rice production, labor, fertilizer, weather conditions, and planting seasons. The study also evaluates the cost reductions achieved through the use of solar-powered irrigation systems compared to diesel-powered ones.

The Net Present Value (NPV)

The Net Present Value (NPV) is a quantitative measure used to assess the profitability of a project. It represents the difference between the present value of cash inflows and outflows, as explained by Kumar et al. (2020). Researchers argue that a positive NPV indicates a favorable financial shift for the investor, while a negative NPV signals a financial disadvantage. A zero NPV implies that the total income over the project's useful life equals the total expenses. The formula for NPV is:

$$NPV = \sum_{t=1}^{T} \frac{R_t}{(1+r)^t} - I$$

Here, R_t represents the annual cash flow, I denotes the initial investment, and r is the discount rate. In this study, r is set at 7%, reflecting the interest rate imposed by banks for funding solar tube well projects under government agricultural programs. Considering inflation volatility, the growth rate of cash flows is assumed to be zero (Guno & Agaton, 2022; Bukhari et al., 2023; Baksh et al., 2016). The NPV analysis is used to compare both technologies and determine which project offers greater benefits.

The Concept of Payback Period (PP)

The Payback Period is a financial metric that measures the time needed to recoup an investment. It is considered a supplementary economic tool (Reniers et al., 2016). The following model is used to compute the payback period for both solar tube wells and micro-hydroelectric tube wells:

$$PBP = \frac{I}{R_t}$$

Environmental Analysis

To evaluate the environmental impact of a process or activity, researchers use three primary approaches: environmental impact assessment, environmental risk assessment, and life cycle impact assessment (Hauschild, 2014). This study compares diesel tube wells with renewable energy irrigation systems, focusing on their daily effects on greenhouse gas (GHG) emissions. The GHG emissions from diesel-powered irrigation pumps were calculated by multiplying the emission factor (EF) or CO2 equivalent by the mean annual fuel consumption (FC):

FC × EF = GHG

Guno and Agaton (2022) used this equation to compute GHG emissions. In this study, FC represents the average annual diesel consumption for irrigation, while EF is derived from the

Emission Factors for Greenhouse Gas Inventories provided by the United States Environmental Protection Agency (EPA, 2021). To determine air pollutant emissions (APEs), the annual average gasoline consumption was multiplied by the pollution factor (PF):

$APE = FC \times PF$

Here, FC refers to the daily average fuel consumption for irrigation during the overall crop seasons in a year, excluding solar and micro-hydroelectric tube wells. The pollution factor is determined according to the 2021 EPA guidelines, which convert the production factor for greenhouse gas inventories.

Findings and Analysis

Installation Cost for a 10-horsepower solar or hydro tube well

The costs associated with boring are kept consistent to accurately assess the actual effects of both procedures. Data from various market vendors indicate price ranges from Rs. 14,75,000 to Rs. 16,00,000. The variation in costs is attributed to differences in panel quality or the services provided by suppliers. An average rate is used to represent these costs. The data is provided by engineers specializing in the installation of hydro and solar turbines.

Table 1: Installation Cost

Solar-powered water pump		The Hydro powered water pump	
Elements	Value	Elements	Value
Motor 10 HP	Rs.2,75,000	Motor 10 HP	Rs. 90,000
Zeunic Panel 20 of 550 Electric energy	11,00,000	Turbine 10 kW	12, 00,000
VFD (Iinvt)11 KW	60,000	VFD (Iinvt)11 KW	60,000
		Router.	1,90,000
Labour Cost	80,000	Labour Cost	1,70,000
Frame Cost	40,000	Water Tank Cost	2,60,000
Wires or belt	40,000	Wires Cost	36000
Total Installation Cost (Initial Investment)	15,95,000	Total Installation Cost (Initial Investment)	20,06,000

Costs Associated with the Operations of Tube Well

There are no incurred fixed costs as the labor cost remains constant and is not considered an operating expense. The operating cost is calculated solely based on the variable cost. When it comes to solar energy, there are no accompanying operational fees, however, hydroelectric power involves maintenance costs. The monthly expenditure for lubricating the bearings and barrels of the router amounts to approximately Rs. 700. Thus, the annual cost is calculated as follows: 700 × 12 months = Rs.8,400.

Incremental Operating Benefits of Renewable Energy Tube Wells VS Diesel Tube Wells

Renewable technologies offer numerous benefits, including positive impacts on the economy and consumers' lifestyles. Consistent with prior studies (Sadiqa et al., 2021), we focus on the cost-saving advantages related to annual fuel expenditure. It is assumed that solar tube wells operate for approximately 8 hours per day due to limited sunshine exposure, whereas micro-hydroelectric tube wells are not constrained by sunlight and can operate continuously for 24 hours. Allowing for a 4-hour maintenance and rest period, we estimate that a micro-hydroelectric tube well system could function for around 20 hours per day. Additionally, surveys indicate that irrigating 1 hectare of agricultural land requires about 8 hours. Therefore, a 10HP solar bore tube well turbine can irrigate 1 hectare per day, while a micro-hydroelectric bore tube well turbine can irrigate 2.5 hectares per day.

Moreover, we focused on the practical capacity of the tube wells rather than their theoretical capacity. For simplicity, we assumed that the tube wells are used for irrigating only two crops per year (wheat and rice). Details about the assumptions and calculations of the incremental operating benefits for both tube well technologies are provided in table 2.

Table 2: Incremental Operating Benefits

(Saving of Fuel Cost)

Particulars	Solar Tube Well	Micro-Hydroelectric Tube Well
Assumption		
Pump Motor HP	10HP	10HP
Running capacity per day	8 Hrs	20 Hrs
1 Hectare irrigation requires time	8 hrs	8hrs
Capacity to irrigate land per day	1 Hectare	2.5 Hectares
Irrigation capacity of 10HP Turbine for ten days	10 Hectares	25 Hectares
Crops per year	Wheat & Rice	Wheat & Rice
Price of Diesel per litre	Rs.290	Rs.290
Watering requirement for wheat crop in a season	4 times	4 times
Irrigation hours for one hectare of wheat crop in a season	4 Times x 8 Hrs=32 Hrs	4 Times x 8 Hrs=32 Hrs
Watering requirement for rice crops in a season	18 times	18 times
Computations		
Irrigation hours for one hectare of rice crop in a season	18 times x 8 hrs= 144 Hrs	18 times x 8 hrs= 144 Hrs
Total irrigation hours provided by tube wells during a year for both crops	(32+144) Hrs x10 Hectares = 1,760 Hrs	(32+144) Hrs x 25 Hectares = 4,400 Hrs
Diesel Consumption per Hr. Quantity of Diesel required per year	2 Litres on average (1,760 Hrs x 2 Litres per Hr) =3,520 Litres	2 Litres on average (4,400 Hrs x 2 Litres) =8,800 Litres
Operating benefit (saving in diesel cost) per year Operating cost of irrigation system per year Incremental operating benefit (savings) per year	3520 Litres x Rs.290 = Rs. 10,20,800 0 = Rs. 10,20,800	8800 Litres x Rs. 290 =Rs. 25,52,000 Rs.8400 Rs. (25,52,000 – 8400) =25,43,600
The economic life of irrigation systems	20-year	20- year
The growth rate of incremental operating savings is assumed zero due to the unpredictable inflation rate over the 20-year life of the irrigation systems		
Total Net Saving over 20 years (life of irrigation tube well system)	(Rs.1020800 x20 Years) =Rs.20,41,600	(Rs. 25,43,600x 20 Years) = Rs. 50,872,000

According to farmer observations, the tube well consumes 2 liters of diesel per hour. A study by Chaudhry et al. (2021) reports a diesel consumption rate of 1.7 liters per hour, while another study by Rizvi et al. (2020) indicates a rate of 2.1 liters per hour for a 10 HP tube well system. These discrepancies are attributed to variations in water depth and area conditions. For our analysis, we assume a diesel consumption rate of 2 liters per hour, with the cost of diesel being Rs. 290 per liter. Results presented in Table 2 show that a 10HP solar tube well turbine provides 1,760 irrigation hours, whereas a micro-hydroelectric tube well turbine offers 4,400 irrigation hours for wheat and rice crops in one year. This suggests that micro-hydroelectric tube well systems have a higher practical capacity for irrigating agricultural land and offer greater operating benefits in terms of fuel savings compared to solar tube well systems. Specifically, the micro-hydroelectric tube well system generates incremental operating benefits per year amounting to Rs. 25,43,600 per year, which is more than double the operating benefit of the solar tube well system.

Results of Economic Analysis

Financial data were analyzed using the benefit-cost ratio, return on investment, net present value, internal rate of return, and payback period to compare solar and micro-hydroelectric tube well systems. The economic analysis utilizes initial investment data from table 1 (installation cost) and operating costs and benefits from table 2. Both tube well technologies are assumed to have a 20-year economic life. The present value of annual operating benefits and costs is discounted using the bank's 7% financing rate for solar panel installation. The economic analysis was conducted using financial models described in subsection 3.2 of the approach. The results of the economic analysis are reported in table 3. The data in Table 3 show that the benefit-cost ratio for solar tube systems is 6.7, while the ratio for micro-hydroelectric systems is 12.9. This indicates that the benefits of integrating micro-hydroelectric and photovoltaic energy outweigh the individual costs of each technology. Solar tube systems, with a benefit-cost ratio above 1, suggest a positive economic impact. Both solar and hydro systems are economically viable, as the benefit-cost ratio for solar tube systems exceeds 1. Bakhsh et al. (2015) noted that the economic feasibility of tube well systems relying on renewable energy would be further enhanced by future increases in fuel prices.

The return on investment (ROI) for the solar option is 578%, while the hydro option stands at 1248%. This significant difference indicates that micro-hydroelectric tube well technology could yield a larger long-term profit, making it a more viable financial alternative. Furthermore, the micro-hydroelectric option has a substantially larger net present value (NPV) of Rs. 1,43,75,901 compared to Rs. 92,19,370 for solar systems. Given this difference, the hydro option appears to be more profitable in the long term. The internal rate of return (IRR) is 53.2% for solar energy, while hydro energy boasts an IRR of 107.3%. A higher IRR suggests a better return on investment, supporting the case for micro-hydroelectric tube well technology. Additionally, the payback period for hydroelectric power is 0.78 years, compared to 1.56 years for solar energy, indicating that the micro-hydroelectric option recovers the initial expenditure faster.

Overall, micro-hydroelectric tube well technology demonstrates superior ROI, NPV, IRR, and a shorter payback period compared to solar tube wells, suggesting that it may be a more advantageous investment. These findings support the economic viability of micro-hydroelectric tube wells as a more sustainable and cost-effective alternative to solar tube wells, particularly when considering long-term fuel savings and operational efficiency.

Table 3: Results of economic analysis

Particulars	Solar Tube Well	Micro-Hydroelectric Tube Well
Incremental operating benefit (savings) per year	= Rs. 10,20,800	Rs. 25,43,600
The economic life of irrigation systems	20-year	20- year
The growth rate of incremental operating savings is assumed zero due to the unpredictable inflation rate and fuel prices over the 20-year life of the irrigation systems.		
Total incremental operating savings over the life of the irrigation tube well system	(Rs.1020800 x20) =Rs.20,41,600	(Rs. 25,43,600x20) = Rs. 50,872,000
Discount Rate (assumed equal to the solar tube well financing rate)	7%	7%
Present value of annual incremental operating benefit (saving of fuel cost)	1,08,14,370	2,70,35,924
Initial Investment (Cost of Installation)	15,95,000	20,06,000
Benefit-Cost t Ratio (BCR)	6.7 Times	12.9 Times
Return on Investment (ROI)	578 %	1248 %
Net Present Value (NPV)	9219370	14375901
Internal Rate of Return (IRR)	53.27%	107.3%
Payback Period (PP)	1.01 years	0.51 years

Results of Environmental Impact Analysis

For the environmental impact analysis, greenhouse gas (GHG) and air pollutant emissions were calculated using the models described in subsection 3.3 of the methodology. Following Karimi et al. (2012), we determined GHG emissions using a factor of 0.73 kg CO2 per liter of diesel. According to Guno and Agaton (2022), we applied the 2014 EPA pollutant factor (PF) of 0.0004 kg per liter of fuel. Table 4 presents the GHG and PF data for both solar and micro-hydroelectric tube wells.

The results of the environmental impact analysis are detailed in Table 4. The research indicates that micro-hydroelectric tube wells would reduce greenhouse gas emissions by 6.424 tons per year and air pollutants by 352 kg per year. In contrast, solar tube wells would decrease greenhouse gas emissions by 2.53 tons per year and air pollutants by 14.8 kg per year. This suggests that micro-hydroelectric tube wells are more effective in reducing greenhouse gas emissions compared to solar tube wells. Consequently, micro-hydroelectric tube wells contribute more significantly to reducing environmental contamination. Additionally, micro-hydroelectric technology saves more diesel annually than solar tube well technology, enhancing its environmental benefits.

Table 4: Results of environmental impact analysis

Particulars	Solar Tube Well System	Micro-hydroelectric Tube Well System
A greenhouse gas emission	GHG = FC × EF =(3520 Litre x 0.73 Kg)/1000 =2.53 Ton	GHG = FC × EF =(8800 Litre x 0.73 Kg)/1000 =6.424 Ton
Air Pollutant Emissions	APE = FC × PF = 3520 Litre x 0.004Kg =14.8 Kg	APE = FC × PF =8800 Litre x 0.004 Kg =35.2 Kg

Conclusion

This study compared two renewable energy-based irrigation methods—solar tube wells and micro-hydroelectric tube wells—to determine which is more financially and environmentally sustainable. We analyzed survey data from farmers and agri-engineering enterprises for both economic and environmental insights. The results indicate that micro-hydroelectric tube wells can irrigate a larger area and operate longer each day compared to solar tube wells of the same capacity. Despite their higher installation, operation, and maintenance costs, micro-hydroelectric systems offer greater irrigation coverage due to their extended daily operation. Economic analysis revealed that micro-hydroelectric tube wells are more cost-effective than solar tube wells, boasting higher Net Present Value (NPV) and Internal Rate of Return (IRR), and a lower payback period.

From an environmental perspective, both systems have minimal impact. Solar technology emits very little CO2, while micro-hydroelectric systems emit zero CO2 and can further reduce diesel consumption and CO2 emissions compared to solar systems. Consequently, micro-hydroelectric tube wells are environmentally superior.

Although solar technology is valuable, it is less effective than micro-hydroelectric technology due to time constraints. The study suggests that micro-hydroelectric systems are more sustainable. To enhance economic and environmental benefits, it is recommended that government and financial institutions extend similar support and subsidies to micro-hydroelectric tube well technology as they do for solar irrigation systems. Credit subsidies and governmental encouragement for micro-hydroelectric technology would support its adoption.

Limitations, and Future Research Direction

The study's conclusions should be interpreted with caution due to certain assumptions and constraints. First, the focus was limited to Lahore, potentially overlooking variations in other cities. Second, variations in turbine motor capacity, irrigation time, diesel consumption, crop types, and pricing factors could affect results. Lastly, regional differences in rainfall, canal water supply, temperature, and groundwater levels may influence findings. Future research should consider these variables to validate the study's results.

Additionally, further research should compare other renewable energy sources such as wind and biogas to determine the most sustainable and economically viable solutions. Examining the impact of renewable irrigation systems on agricultural produce prices, farmer income, and consumer welfare is also recommended. A pilot study installing both solar and micro-hydroelectric tube wells on the same farm could clarify the distinctions between these systems. Future studies could also explore the societal impacts of renewable energy through qualitative research to assess its effects on communities and farmers.

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