Assessment of the Cost-effectiveness and Environmental Sustainability of Mini Micro Hydro Power Projects in Khyber Pakhtunkhwa, Pakistan

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Abstract

This research paper investigates the socio-economic impact of Mini Micro Hydro Power (MHP) projects in the Upper Kalam area of the Utror Valley, Swat, within the province of Khyber Pakhtunkhwa (KP), Pakistan. It conducts a comprehensive analysis of the economic and environmental aspects of MHP, comparing it with the traditional electricity supplied by WAPDA. The study utilizes field survey data to evaluate factors such as income sources, land ownership, energy consumption patterns, and monthly expenses related to electricity. The findings suggest that MHP installations contribute to reduced greenhouse gas emissions, lower energy expenses, and positive economic outcomes for users. Financial analysis indicates the cost-effectiveness and viability of MHP projects, with sensitivity analysis demonstrating resilience to capital cost fluctuations. Moreover, an environmental assessment highlights the role of MHP in promoting clean energy and reducing CO_2 *emissions. The paper concludes with policy recommendations aimed at leveraging MHP projects for sustainable development in the region.*

Keywords: Mini Micro Hydro Power, Socioeconomic Conditions, Greenhouse Gas Emissions, Clean Energy, CO_2 Reduction, Viability.

Introduction

The world is changing to the renewable energy sources to lower its cost. Mini Micro Hydro Power projects are very important for fulfilling and in addressing energy challenges in Khyber Pakhtunkhwa, particularly in remote and mountainous areas. These projects are crucial in providing sustainable and reliable energy solutions to regions that are often underserved by the national grid. The region's geographical and socio-economic characteristics necessitate innovative approaches to energy provision, making the study of Mini Micro Hydro Power highly relevant.

Research gaps identified from existing literature provide a roadmap for future studies, focusing on areas such as comparative analysis with other renewable energy technologies, regional variability, and long-term sustainability. These gaps highlight the need for a deeper understanding of how Mini Micro Hydro Power projects can be optimized

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and integrated into broader energy strategies. The problem statement addresses critical issues surrounding the feasibility, sustainability, and broader implications of MHP projects, underscoring the necessity for further research and policy interventions. This sets the stage for exploring the practical challenges and potential benefits of implementing these projects in the region. Moreover, research questions are formulated to address the reliability and cost-effectiveness of Micro Hydro Power for decentralized power distribution. By focusing on these aspects, the study aims to provide insights into the operational and economic viability of these projects.

The objectives of the study are delineated to assess the cost-effectiveness and environmental sustainability of Mini Micro Hydro Power. These objectives guide the research towards evaluating the dual benefits of economic efficiency and ecological preservation. Likewise, hypotheses to be tested affirm Micro Hydro Power as an environmentally sustainable energy source and a cost-effective strategy for rural electrification. Testing these hypotheses provide evidence to support the broader adoption of Mini Micro Hydro Power projects. This chapter sets the stage for the subsequent sections, laying the foundation for a comprehensive examination of the socioeconomic impact of Mini Micro Hydro Power projects in Khyber Pakhtunkhwa. By addressing these key areas, the research aims to contribute valuable knowledge to the field of sustainable energy development.

Micro Hydro power stands as a decentralized energy source providing rural households with doorstep energy solutions. It eliminates the need for water storage and can be implemented on small rivers, streams, and canals. Reddy (1999) analyzed the goals, strategies, and policies related to rural energy, highlighting its historical neglect in India. Before the 1970s, India focused on centralized electricity generation with minimal use of indigenous resources. Post-1970s, there is a shift towards rural energy, linking it with poverty alleviation and human development, particularly through the Human Development Index (HDI). Reddy emphasized the unique challenges of rural populations, which make urban energy approaches costly and inefficient.

Woodruff (2007b) conducted an economic evaluation of renewable energy options for rural electrification in Pacific Island nations, focusing on micro hydro power projects. The study used least cost analysis but acknowledged the difficulties in measuring indirect benefits such as improved education from extended study hours. The potential environmental benefits are not evaluated. Wazed and Ahmed (2008) analyzed Micro Hydro power in Bangladesh, identifying its underutilized yet proven potential. Their study concluded that Micro Hydro power plants could significantly contribute to the country's energy generation. Sheikh (2010) examined the energy and renewable energy scenario in Pakistan, highlighting the sector's importance and suggesting the use of indigenous technology. Farooq and Kumar (2013) assessed Pakistan's potential to generate more electricity from renewable sources than from conventional ones.

Existing literature primarily focuses on cost-benefit analysis, local sustainability impacts, community participation, feasibility studies, and the potential for renewable energy in rural communities. While numerous studies have been conducted in India, Nepal, and China, limited work has been done in Pakistan. This study aims to address this gap by calculating emission reductions and emphasizing the importance of small-scale, clean energy projects in Pakistan compared to large-scale, fuel-based power projects. The conceptual framework of this thesis centers on Micro Hydro Power (MHP) projects as decentralized energy solutions for rural Pakistan. It builds on existing literature, addressing identified research gaps.

Micro Hydro Power is considered a clean and small-scale energy solution for rural areas in Pakistan, focusing on several key dimensions:

Financial and Economic Aspects

- Financial indicators such as NPV, BCR, IRR, and Payback Period.
- Long-term economic and financial sustainability.
- Impact of inflation, changing energy market dynamics, and evolving technology.

Environmental Impact

- Reduction of emissions (CO_2 eq).
- Broader environmental consequences beyond CO_2 emissions, including water quality, habitat preservation, and ecosystem health.

Social Implications and Community Engagement

- Issues such as land disputes, unskilled operators, and institutional arrangements.
- Opportunities for employment, community engagement, and involvement of local stakeholders.

This study includes a comparison with other renewable energy technologies (solar, wind, biomass) and assessments of cost and sustainability in different contexts. Finally, this section proposes practical policy recommendations to promote the adoption and implementation of Micro Hydro Power projects in rural Pakistan, considering their economic, environmental, and social benefits.

Methodology

Research Design and Nature

This research employs a mixed methods approach of quantitative and qualitative strategies to assess Micro Hydro Power (MHP) schemes in rural Pakistan. Its chosen study area is the Utror Valley area, Kalam in Swat, Khyber Pakhtunkhwa (KPK), as it has a high density of MHP units.

Data Collection and Sampling Technique

The methodology delineates the comprehensive procedures involved in data acquisition and analysis for evaluating Micro Hydro Power (MHP) projects in the context of rural Pakistan. The study combines both primary and secondary data sources. Primary data are collected through structured questionnaires designed for households and MHP plants in the Utror valley, Kalam, Swat, Khyber Pakhtunkhwa (KPK). These questionnaires aimed to gather information on household energy consumption patterns, socioeconomic factors, and the operational aspects of MHP plants. Separate sets of questionnaires are used for households connected to MHP units and those relying on WAPDA electricity. Additionally, interviews are conducted with MHP plant operators to gather data on plant specifications and operational challenges. The study area, Utror valley, is selected due to its significant presence of MHP units catering to local household electricity needs. Sampling involved categorizing households based on their electricity sources and selecting representative samples from each category. A total of 100 households from MHP-connected and WAPDA-connected categories are chosen, along with 25 operational MHP plants. The sample size is determined using a sample size calculator to ensure statistical robustness.

Quantitative data collection employed a combination of structured questionnaires and participatory tools such as Focus Group Discussions (FGDs) and Key Informant Surveys (KIS). These methods aimed to extract meaningful insights, validate quantitative findings, and explore underlying issues related to MHP projects and household energy consumption. Before the main survey, a pretesting phase is conducted in the field to assess the effectiveness of the questionnaire. Insights gained during this phase led to questionnaire modifications and adjustments to ensure data accuracy and relevance.

Data Analysis

The methodology involves a multi-faceted analysis encompassing descriptive, financial, economic, and environmental aspects of MHP projects. Descriptive analysis examines household energy consumption patterns, while financial and economic analyses evaluate the economic viability and sustainability of MHP projects. An environmental analysis assesses the emission reduction benefits of MHP compared to traditional energy sources. Quantitative data collected from households and MHP plants underwent a descriptive analysis using the Statistical Package for Social Scientists (SPSS). The analysis focused on various factors including household demographics, income sources, energy consumption patterns, and satisfaction levels with MHP and WAPDA electricity. Additionally, the analysis compared energy costs and usage between MHP-connected and WAPDA-connected households, highlighting the benefits of MHP in reducing dependency on alternative energy sources.

Financial analysis involved assessing the operational cash flows and costs associated with MHP projects. Key financial metrics such as Net Present Value (NPV), Benefit Cost Ratio (BCR), Internal Rate of Return (IRR), and Payback Period (PBP) are calculated to determine the project's financial viability and return on investment. Economic analysis adjusted financial values to reflect true societal costs and benefits using standard conversion factors. The environmental analysis focused on assessing the emission reduction benefits of MHP projects compared to traditional energy sources. By replacing fossil fuels, MHP projects contribute to reducing greenhouse gas emissions, thus aiding in environmental preservation.

Data Analysis and Results

Analysis and discussion present an economic and environmental evaluation of Micro Hydro Power (MHP) plants in the Upper Kalam area of the Utror Valley, Swat, Khyber Pakhtunkhwa. The analysis is divided into four sections: descriptive statistics of the study's primary variables, cost comparison between WAPDA electricity and MHP plants, financial and economic analysis, and environmental impact assessment of MHP plants.

The primary sources of income for households using MHP include daily wage employment (45%), agriculture (27%), services (23%), business (3%), and overseas employment (2%). The remote and hilly nature of the area limits accessibility to business and overseas employment opportunities. In contrast, non-MHP households have a lower percentage engaged in agriculture and manual labor but higher involvement in services, business, and overseas employment. MHP user households possess larger agricultural land holdings compared to non-MHP households, indicating a greater reliance on agriculture. The distribution of land holdings among MHP and non-MHP households is outlined in Table 1.

Table 1: Comparison of Income Sources Between MHP and Non-MHP Households.

Income Source	MHP Households (%)	Non-MHP Households (%)
Daily Wage	45	40
Agriculture	27	20
Services	23	30
Business	3	7
Overseas Employment	2	3

MHP users rely primarily on MHP (76%) for lighting, while non-MHP households use a mix of WAPDA (13%), kerosene oil (31%), solar cells (32%), and generators (24%). MHP users report significantly longer daily electricity availability compared to non-MHP users. MHP users have electricity available for 10-12 hours (92%) and 14-18 hours (8%), whereas non-MHP users have it for 3-4 hours (97%) and 5-6 hours (3%). MHP households incur lower monthly bills and connection charges compared to WAPDA-connected households. The monthly bills for MHP users range from Rs. 200 to Rs. 500, with an average of Rs. 350, and connection charges range from Rs. 1200 to Rs. 8000, with an average of Rs. 4600. In contrast, WAPDA users have monthly bills ranging from Rs. 600 to Rs. 3500, with an average of Rs. 2050, and connection charges from Rs. 6000 to Rs. 8000, with an average of Rs. 7000.

Table 2: Electricity Source Usage Among MHP and Non-MHP Households.

Electricity Source	MHP Households (%)	Non-MHP Households (%)
MHP	76	0
WAPDA	0	13
Kerosene Oil	0	31
Solar Cells	0	32
Generators	0	24

Note. MHP users primarily rely on MHP, while Non-MHP users use a mix of sources.

Table 3: Daily Electricity Availability for MHP and Non-MHP Users.

Availability (Hours)	MHP Households (%)	Non-MHP Households (%)
3-4	0	97
5-6	0	3
10-12	92	0
14-18	8	0

Note. MHP users have longer daily electricity availability compared to Non-MHP users.

Table 4: Monthly Electricity Bills and Connection Charges for MHP and WAPDA Users.

Cost Type	MHP Households (Rs.)	WAPDA Households (Rs.)
Monthly Bill (Range)	200 - 500	600 - 3500

Cost Type	MHP Households (Rs.)	WAPDA Households (Rs.)
Monthly Bill (Avg.)	350	2050
Connection Charge (Range)	1200 - 8000	6000 - 8000
Connection Charge (Avg.)	4600	7000

Note. MHP users have lower monthly bills and connection charges than WAPDA users.

Table 5: Electricity Cost per Unit for MHP and WAPDA Users.

Electricity Type	Cost Per Unit (Rs.)	Monthly Bill for 150 kWh (Rs.)
MHP	2.33	350
WAPDA	9.00	1350

Note. MHP electricity is significantly cheaper per unit compared to WAPDA electricity.

An average MHP plant with a 30-kWh capacity operates for 10 hours daily, producing 300 kWh of energy. Given an average household consumption of 5 kWh/day (150 kWh/month), the cost per unit of electricity from MHP is Rs. 2.33. For WAPDA electricity, the cost per unit is Rs. 9 for households consuming 100-200 kWh per month, resulting in a monthly bill of Rs. 1350 for a household using 5 kWh/day (150 kWh/month).

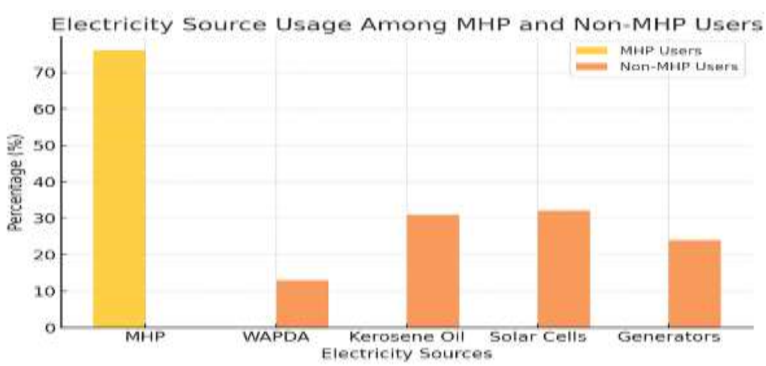

Figure 1: Electricity Source Usage Among MHP and Non-MHP Users.

The financial analysis shows the Financial Internal Rate of Return (FIRR) for MHP at 24%, which is higher than the discount rate of 13%, indicating financial viability. The Economic Internal Rate of Return (EIRR) is 27%, reflecting broader economic benefits. The positive Net Present Value (NPV) and Benefit-Cost Ratio (BCR) greater than one further confirm the project's feasibility. The payback period for financial analysis is five years, while for economic analysis, it is three and a half years, showing that MHP projects provide quick returns on investment.

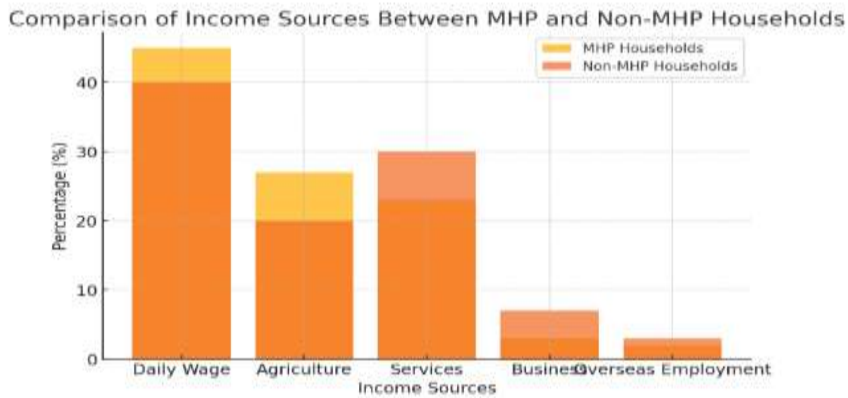

Figure 2: Comparison of Income Sources Between MHP and Non-MHP Households.

MHP-connected households use significantly less fossil fuel compared to non-MHP households, leading to reduced greenhouse gas emissions and a smaller carbon footprint. This contributes to environmental sustainability and mitigates climate change impacts. Reduced reliance on kerosene oil and diesel reduces indoor air pollution, decreasing health risks such as lung diseases, bronchitis, and asthma. This enhances the overall well-being of the community. MHP users report higher satisfaction levels compared to WAPDA users. Among MHP users, 30% are extremely happy, 50% are satisfied, 10% are neutral, and 10% are unhappy, with none extremely unhappy. In contrast, WAPDA users have 0% extremely happy, 20% satisfied, 10% neutral, 35% unhappy, and 35% extremely unhappy.

The findings indicate that Micro Hydro Power is a reliable, cost-effective, and environmentally sustainable source of energy for decentralized power distribution in rural areas. MHP users benefit from lower energy costs, greater electricity availability, and reduced environmental and health impacts. The financial and economic analyses further validate the viability and profitability of MHP projects, making them an attractive option for rural electrification.

Discussion

The analysis shows that Micro Hydro Power (MHP) systems contribute to transforming the socioeconomic and environmental situation of Upper Kalam, Utror Valley, Swat. The household's dependent on MHP appear more involved in agricultural activities (27%) and manual labor (45%) because of the rural and mountainous area. Reddy (1999) made the connection that localized renewable energy systems are used most effectively when they fit the local livelihoods and land use patterns within rural communities.

MHP users benefit from higher energy security, with longer periods of electricity supply (10-18 hours per day), than non-MHP users who receive electricity for only 3-6 hours a day. This discrepancy significantly increases productivity and quality of life, which is consistent with the findings of Paish (2002) and González et al. (2009) who reported access to electricity in remote communities improved not only household welfare, but also supported development.

With regard to costs, MHP uses electricity that is much cheaper, costing Rs. 2.33 per unit compared to Rs. 9.00 for WAPDA. The affordability of MHP supports Greenstone's (2014) claim that the cost-effective provision of energy can spur growth and development through inclusivity. It is also worth mentioning that the connection fee of Rs. 4600 and a monthly bill of Rs. 350 make MHP an economic possibility, particularly in areas where grid connections are unavailable or too expensive (Farooq & Kumar, 2013).

The financial and economic indicators provide further evidence of the viability of MHP projects. The projects have a Financial Internal Rate of Return (FIRR) of 24% and a Economic Internal Rate of Return (EIRR) of 27%, significantly exceeding the standard discount rate of 13% when are used as a points of the Green Bank compensation per Watt (Bierman & Smidt, 2012; Edvard, 2011). The Net Present Value (NPV) and the Benefit-Cost Ratio (BCR > 1) support their asserted profitability and utility of the systems, and align with the standards in the development economics literature (European Commission, 1997; The World Bank, 2005).

MHP also plays a significant role in environmental sustainability. Given that biomass-based energy systems like kerosene oil and diesel ultimately have carbon emissions of similar magnitude, switching to clean hydropower greatly reduces carbon emissions and indoor air pollution, which in turn reduces climate-related health problems like asthma and bronchitis (Akella, Saini, & Sharma, 2009; Jaffrey, 2013). As Condrea & Bostan (2008) noted, "not only do renewable energy projects reduce the ecological footprint, they will, according any combination of cost savings and related health benefits, improve the community health status on the road to sustainability" (pg. 329).

The reported level of satisfaction indicates the level of social acceptance and perceived benefits derived from use of MHP. With 80% of all MHP users rating it as satisfactory or better satisfaction versus 20% of smartphone users (WAPDA), the overall results are consistent with the principles of participatory development regarding the importance of community-centred infrastructure planning (Chambers, 1994; Khennas & Barnett, 2000), Furthermore, the decentralized aspect of MHP adds to energy sovereignty and encourages local communities to manage their own energy needs, a concern that Pandey (2008) and Shakya (2011) raised when advocating for community-based renewable energy as a sustainable development approach in mountainous and remote regions.

In a broader lens of Pakistan's energy policy, our results reinforce the need to diversify the country's energy mix with localized renewable sources like MHP, especially in underdeveloped regions (Government of Pakistan, 2013; Sheikh, 2010). The MHP model also aligns with the aims of Pakistan's National Power Policy and its climate obligations to international frameworks, such as the Clean Development Mechanism (Ahmad & Salman, 2012; UNFCCC, n.d.).

Conclusion and Policy Recommendations

In summary, Mini Micro Hydro Power (MHP) systems in Utror Valley, Upper Kalam, Swat are reasonably and sustainable solutions for rural electrification, providing benefits for both socioeconomics and the environment. There is a total of 1.058 MW installed capacities, with the majority being private sector MHP developments. MHP systems increase electricity access, limit fossil fuel consumption, lower household energy expenditure and better health outcomes due to a reduction in emissions. Households that utilized MHP obtained more hours of electricity usage per day, had lower monthly bills, lower connection fees and had a better quality of life due to greater access to energy and better sources of lighting. To foster a smoother transition into widespread adoption of MHP systems, the government is encouraged to offer financial incentives such as targeted subsidies, promote community based technical training, and undertake knowledge sharing to promote public acceptance. Policies can also strengthen community engagement for the sustainability of MHP systems. Future research needs to address limitations such as the small sample size, and look at longitudinal effects, community engagement, and consider how to integrate MHP development into a wider policy climate, such as national sustainability and development frameworks.

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