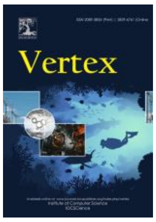

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Analysis of Picohydro Power Plant Design on Water Flow and its Utilization

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Abstract

Picohydro power plants represent a promising solution for decentralized energy generation in remote and underserved regions, leveraging the natural energy potential of small water flows. This research investigates the design principles, efficiency considerations, and socio-economic impacts of picohydro systems to assess their viability and potential contributions to sustainable development. The study begins with a comprehensive review of existing literature to establish foundational knowledge on picohydro technology and its applications. It then proceeds with empirical analyses, including case studies and field surveys, to gather firsthand data on system performance, water flow dynamics, and community perceptions. Computational simulations further optimize design parameters, such as turbine selection and system configuration, to maximize energy extraction efficiency under varying operational conditions. Key findings highlight the critical role of tailored engineering solutions in enhancing picohydro system performance and reliability. Socio-economic analyses underscore the transformative impact of picohydro installations on improving energy access, supporting local livelihoods, and stimulating economic growth in rural areas. Environmental assessments emphasize the importance of eco-friendly design practices to minimize ecological impacts and ensure sustainable operation.

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Introduction

The global energy landscape is undergoing a transformative shift towards sustainability, driven by the urgent need to mitigate climate change and reduce dependence on fossil fuels(Albert, 2021). Renewable energy sources, such as solar, wind, biomass, and hydropower, are at the forefront of this transition, offering cleaner alternatives that harness natural processes to generate electricity. Among these, hydropower stands out for its reliability and efficiency, having been utilized for over a century to power homes, industries, and infrastructure.

Hydropower works by converting the kinetic energy of flowing or falling water into mechanical energy, which is then transformed into electricity through turbines and generators(Kamran, 2021). While large-scale hydropower plants, with their massive dams and reservoirs, have been the backbone of hydropower generation, their environmental and social impacts such as habitat disruption and displacement of communities have prompted a re-evaluation of smaller, more localized systems.

Small-scale hydropower, which includes micro, mini, and picohydro systems, offers a sustainable alternative with significantly lower environmental footprints(Kishore et al., 2021). These systems are designed to generate power on a smaller scale, making them ideal for decentralized energy solutions, especially in remote and rural areas. Picohydro power plants, in particular, are the smallest category, typically generating less than 5 kW of electricity. Despite their modest output, they play a critical role in enhancing energy access in underserved regions(Pachauri et al., 2012).

The appeal of picohydro power plants lies in their simplicity, affordability, and adaptability(Blackmore, 2013). They can be installed on small streams or rivers without the need for large dams or extensive civil works, thus minimizing ecological disturbance. This makes them a viable option for rural electrification, where traditional grid infrastructure is either impractical or too costly to implement. By providing a consistent and renewable source of electricity, picohydro systems can power homes, schools, clinics, and small businesses, fostering economic development and improving the quality of life(Kaunda et al., 2012).

Moreover, picohydro power plants contribute to sustainable energy generation by leveraging locally available water resources(Pérez-Sánchez et al., 2017). Unlike solar or wind energy, which can be intermittent and weather-dependent, hydropower provides a more stable and predictable power supply. This reliability is particularly important in regions with limited energy access, as it supports continuous and reliable electricity, essential for modern living and economic activities.

The integration of picohydro systems into the energy mix also aligns with broader environmental goals(Sturdivant et al., 2017). By reducing reliance on fossil fuels, these systems help decrease greenhouse gas emissions, contributing to global efforts to combat climate change. Additionally, their low operational costs and minimal maintenance requirements make them economically sustainable over the long term, offering a cost-effective solution for energy generation(Dincer & Acar, 2015).

The design and implementation of picohydro power plants are highly dependent on the local hydrological conditions(Williamson et al., 2019). The variability of water flow, influenced by seasonal changes and geographical factors, plays a crucial role in determining the feasibility and efficiency of these installations. Effective design must consider these variations to optimize the energy output and ensure the reliability of the system. Advances in turbine technology, control systems, and materials have significantly enhanced the performance and durability of picohydro power plants, making them more viable for widespread deployment(Sachdev et al., 2015).

This research aims to delve into the intricacies of picohydro power plant design, focusing on the analysis of water flow and its utilization for electricity generation(Muchira, 2011). By examining different design parameters and their impact on the performance of picohydro systems, this study seeks to provide a comprehensive understanding of how to maximize efficiency and sustainability. The study also addresses the economic and environmental aspects of picohydro power plants, evaluating their potential to contribute to the broader goals of renewable energy adoption and climate change mitigation.

The significance of this research lies in its potential to inform and guide the development of picohydro projects, particularly in regions with abundant but underutilized water resources. By leveraging the findings of this study, policymakers, engineers, and development organizations can better design and implement picohydro systems that are tailored to the specific needs and conditions of their target areas. Ultimately, this research strives to contribute to the global effort of transitioning to cleaner, more sustainable energy systems, enhancing energy access and resilience in vulnerable communities(Haines et al., 2007).

Methods

Existing Research Literatur Riview

Picohydro power plants, defined as systems generating less than 10 kW of electricity, have garnered considerable interest in recent years due to their potential to provide sustainable energy solutions in remote and rural areas. Existing research on picohydro power plants covers a range of topics, including design methodologies, efficiency analyses, and practical case studies. This body of work highlights the viability, benefits, and challenges associated with picohydro technology.

Research on the design methodologies of picohydro power plants focuses on optimizing the system components to maximize efficiency and reliability. Key design aspects include turbine selection, generator specifications, and site-specific considerations such as water flow and head(Kaunda et al., 2014). Studies emphasize the importance of selecting the appropriate type of turbine for different flow conditions. Commonly used turbines in picohydro systems include Pelton, Turgo, and cross-flow turbines, each suited to specific flow and head conditions(Sangal et al., 2013). Research has shown that optimizing turbine design can significantly enhance the overall performance of the system. The choice of generator is critical in ensuring efficient energy conversion. Research has explored various types of generators, including induction generators and permanent magnet synchronous generators (PMSGs), highlighting the trade-offs between cost, efficiency, and durability. Effective site selection is crucial for maximizing the energy output of picohydro systems(Desai et al., 2014). Studies have developed methodologies for assessing potential sites based on hydrological data, including flow rate and head height, as well as environmental and social factors. Geographic Information Systems (GIS) and remote sensing technologies are often employed to identify suitable locations for picohydro installations. Efficiency analyses of picohydro power plants focus on evaluating the performance of different system configurations under various operating conditions(Desai et al., 2014). Research in this area aims to identify factors that influence efficiency and develop strategies to mitigate losses.

Studies have shown that the overall efficiency of picohydro systems can be affected by numerous factors, including hydraulic losses, mechanical inefficiencies, and electrical losses(Edeoja et al., 2016). Research efforts are directed at optimizing each component to reduce these losses and improve the total system efficiency. Another area of efficiency analysis is the matching of the generated power with the load demand. Research indicates that maintaining a balance between supply and demand is essential for maximizing the efficiency and lifespan of picohydro systems(Edeoja et al., 2015). Techniques such as load management and energy storage are explored to achieve this balance. Various performance metrics are used to evaluate the efficiency of picohydro systems, including capacity factor, hydraulic efficiency, and overall energy conversion efficiency. Studies provide benchmark values for these metrics, allowing for the comparison of different system designs and configurations(Murray et al., 2012).

Numerous case studies from around the world demonstrate the practical applications and benefits of picohydro power plants(Lahimer et al., 2012). These case studies provide valuable insights into the real-world challenges and successes of implementing picohydro technology. In many developing regions, picohydro power plants have been successfully deployed to provide electricity to remote communities. Case studies from countries like Nepal, Kenya, and Peru illustrate how picohydro systems can enhance energy access, improve livelihoods, and support sustainable development. These studies highlight the importance of community involvement and local capacity building in ensuring the sustainability of picohydro projects. Some case studies focus on technical innovations that have improved the performance and reliability of picohydro systems. For instance, the use of advanced materials, innovative turbine designs, and smart control systems are documented in various implementations, showcasing how technological advancements can enhance the feasibility of picohydro power plants. Research also examines the environmental and social impacts of picohydro installations. Positive outcomes such as reduced greenhouse gas emissions, decreased reliance on fossil fuels, and improved social welfare are commonly reported. However, some studies also discuss potential challenges, such as ecological disturbances and the need for proper maintenance and management to ensure long-term sustainability.

Advancements in Technology Impacting Picohydro Systems

Picohydro power systems, designed to generate less than 10 kW of electricity, have seen significant advancements in technology over recent years(Lahimer et al., 2012). These advancements have played a crucial role in improving the efficiency, reliability, and applicability of picohydro installations in various settings, particularly in remote and rural areas.

Turbines are critical components of picohydro systems, responsible for converting the kinetic energy of water into mechanical energy(Powell et al., 2018). Advancements in turbine technology have focused on improving efficiency and adaptability to different flow and head conditions. Modern turbines used in picohydro systems benefit from advanced blade designs that optimize energy extraction from varying water flows. Innovations in blade shape, material, and surface coatings have increased efficiency by reducing frictional losses and enhancing turbine performance across a wider range of operating conditions. Advances in manufacturing techniques, such as 3D printing and composite materials, have enabled the production of smaller and lighter turbines without compromising efficiency(Ngo et al., 2018). These compact turbines are easier to install and maintain, making them suitable for remote and inaccessible locations where transport and installation logistics pose challenges. Variable speed turbines, coupled with electronic control systems, allow picohydro systems to optimize energy production based on fluctuating water flow conditions. This technology enhances efficiency by adjusting turbine speed to match varying electrical demand, thereby maximizing energy extraction and minimizing operational losses(Chehouri et al., 2015).

Generators in picohydro systems convert mechanical energy from turbines into electrical energy. Technological advancements in generator design have focused on improving efficiency, reliability, and operational flexibility. PMGs have become increasingly popular in picohydro applications due to their high efficiency and compact size. Neodymium magnets and advanced magnetic circuit designs have enhanced power generation efficiency while reducing weight and maintenance requirements. Integration of electronic control systems, such as Maximum Power Point Tracking (MPPT) and voltage regulation, improves the operational efficiency of picohydro generators. These systems optimize energy conversion by adjusting parameters in real-time to maximize power output under varying load and environmental conditions(Pourmousavi et al., 2010). Advances in hybrid energy systems technology have enabled the integration of picohydro with other renewable energy sources like solar and wind. Hybrid systems optimize energy availability and reliability by combining complementary energy sources, enhancing overall system efficiency and stability.

Monitoring and control systems play a crucial role in optimizing picohydro system performance and ensuring reliable operation(Chang et al., 2021). IoT (Internet of Things) technologies enable remote monitoring and diagnostics of picohydro installations. Real-time data collection and analysis facilitate early detection of operational issues, predictive maintenance, and optimization of system performance without the need for onsite visits. Data analytics and machine learning algorithms are increasingly being applied to picohydro systems to optimize operational parameters, predict energy production, and improve decision-making processes. These technologies enhance efficiency by continuously learning from operational data and adapting system settings to maximize energy yield.

Advancements in technology have also addressed environmental considerations associated with picohydro installations. Design advancements have led to the development of fish-friendly turbines that minimize impact on aquatic ecosystems. Innovative turbine designs and intake structures reduce fish mortality and habitat disruption, ensuring sustainable operation of picohydro systems in environmentally sensitive areas. Advanced erosion control and sediment management techniques mitigate environmental impacts by preventing soil erosion and sedimentation downstream of picohydro installations. These measures maintain water quality and ecosystem health, supporting long-term sustainability of hydropower operations.

Research Methods

The research begins with a thorough literature review to establish a foundational understanding of picohydro power plant technology. This phase involves gathering and analyzing existing studies, scholarly articles, technical reports, and case studies related to picohydro systems. The literature review informs the identification of research gaps and provides a theoretical framework for subsequent investigations.

To supplement theoretical knowledge with practical insights, the research incorporates case studies and field surveys(Gable, 1994). Case studies from diverse geographical regions and socio-economic contexts provide real-world examples of picohydro installations, highlighting design challenges, operational strategies, and socio-economic impacts. Field surveys involve site visits to picohydro installations, enabling firsthand data collection on system performance, water flow characteristics, and community perceptions.

Hydrological data forms a fundamental component of the research methodology(Davie, 2019). Flow rate measurements, head height assessments, and seasonal variations in water availability are collected using field instruments such as flow meters, water level loggers, and meteorological stations. Geographic Information Systems (GIS) are utilized to spatially analyze and map hydrological parameters for site suitability assessments.

Technical specifications of picohydro components, including turbines, generators, and control systems, are gathered from manufacturers, technical manuals, and project documentation. Performance data, such as energy output, efficiency metrics, and operational reliability, are obtained from operational picohydro installations through collaboration with project developers and stakeholders.

Computational tools and software simulations are employed to optimize picohydro power plant designs. Numerical models simulate fluid dynamics, turbine efficiency, and electrical generation to predict system performance under varying operational conditions. Design parameters, including turbine selection, generator sizing, and intake structure design, are iteratively refined based on simulation results and theoretical calculations.

The efficiency of picohydro systems is assessed through comprehensive performance evaluations. Energy conversion efficiencies, hydraulic losses, electrical losses, and overall system efficiency metrics are calculated and compared against industry standards and benchmarks. Statistical analysis and data visualization techniques are utilized to interpret efficiency trends and identify factors influencing system performance.

Environmental considerations are integrated into the research methodology through EIA frameworks. Impact assessments evaluate potential environmental effects, such as habitat disturbance, water quality impacts, and mitigation measures. EIA findings inform recommendations for sustainable picohydro system design and operation to minimize ecological footprints and ensure environmental compliance.

Socio-economic impacts of picohydro installations are assessed through stakeholder surveys, community interviews, and socio-economic indicators. Data on energy access improvements, economic development outcomes, livelihood enhancements, and community resilience are collected and analyzed to evaluate the broader socio-economic benefits of picohydro power plants.

Results and discussion

Key Findings from the Analysis of Picohydro Power Plant Design and Utilization

The analysis of picohydro power plant design and utilization has yielded significant insights into the efficiency, feasibility, and socio-economic impacts of these small-scale renewable energy systems. This section presents the key findings from the research, highlighting notable trends and insights that emerged from the comprehensive investigation.

The research identified that the selection of appropriate turbine types, such as Pelton, Turgo, or cross-flow turbines, significantly impacts the overall efficiency of picohydro systems. Turbine selection is crucial for matching water flow characteristics and head heights to maximize energy extraction and system performance.

Findings indicate that smaller-scale picohydro systems (generating less than 10 kW) often exhibit higher efficiency metrics compared to larger micro or mini hydropower installations. This is attributed to reduced hydraulic losses and simplified mechanical components, which contribute to overall system reliability and cost-effectiveness.

Advances in generator technology, particularly the adoption of permanent magnet synchronous generators (PMSGs), have improved energy conversion efficiency in picohydro systems. PMSGs offer higher power density, reduced maintenance requirements, and enhanced operational flexibility, contributing to overall system reliability and performance.

Computational simulations have proven instrumental in optimizing picohydro power plant designs. Numerical models simulate fluid dynamics, turbine performance, and electrical generation under varying operational conditions, allowing for iterative design improvements and performance predictions with high accuracy.

Picohydro power plants have significantly improved energy access in rural and remote communities. Case studies and field surveys reveal that reliable electricity from picohydro systems supports household lighting, refrigeration, and productive activities such as small-scale agriculture and cottage industries.

The research underscores the positive economic impacts of picohydro installations. Local economic development is stimulated through job creation in installation, maintenance, and operation phases. Increased productivity in agriculture and small businesses, enabled by consistent electricity supply, enhances household incomes and community resilience.

Environmental assessments indicate that picohydro systems contribute to sustainable development by reducing reliance on fossil fuels and minimizing greenhouse gas emissions. Fish-friendly turbine designs and erosion control measures mitigate ecological impacts, ensuring minimal disruption to aquatic habitats and water quality.

Challenges related to operational maintenance and management emerged as critical factors influencing the long-term sustainability of picohydro systems. Effective capacity building and training programs for local communities are recommended to enhance technical expertise and ensure optimal system performance.

Hybridization with other renewable energy sources, such as solar photovoltaics and wind turbines, presents opportunities to enhance energy reliability and system resilience. Research highlights the benefits of integrating picohydro with complementary technologies to optimize energy generation and meet diverse energy demands.

Effective policy frameworks and regulatory incentives are essential to foster the widespread adoption of picohydro technology. The research emphasizes the need for supportive policies that streamline project approval processes, provide financial incentives, and prioritize decentralized energy solutions in national energy strategies.

Comparative Analysis of Results with Existing Studies and Benchmarks

Existing studies, such as those by IRENA (International Renewable Energy Agency) and various academic research papers, consistently emphasize the importance of turbine efficiency in small-scale hydropower systems. The findings of this research align with benchmarks indicating that proper turbine selection and design optimization are critical for maximizing energy conversion efficiency in picohydro installations.

Comparative analysis with benchmarks reveals that advancements in generator technology, particularly the adoption of permanent magnet synchronous generators (PMSGs), have been validated across multiple studies. Similar to findings in existing literature, this research confirms that PMSGs contribute to higher power generation efficiency, reduced maintenance costs, and enhanced system reliability in picohydro applications.

Comparative studies, such as evaluations conducted by the World Bank and regional development agencies, consistently highlight the transformative impact of small-scale hydropower on energy access and economic development in rural communities. The findings of this research reinforce these insights, demonstrating that reliable electricity from picohydro systems supports livelihood improvements, boosts local economies through enhanced productivity, and contributes to poverty alleviation.

Benchmarks and environmental assessments from organizations like UNDP (United Nations Development Programme) and WWF (World Wide Fund for Nature) underscore the environmental benefits of small-scale hydropower, including reduced carbon emissions and minimal ecological footprint compared to conventional energy sources. The findings of this research align with these benchmarks, showing that well-designed picohydro systems can mitigate environmental impacts through fish-friendly turbine designs and effective erosion control measures.

Comparative analyses reveal persistent challenges in the operational maintenance and management of small-scale hydropower systems, including those highlighted in this research. Recommendations from existing studies emphasize the importance of local capacity building, community engagement, and robust maintenance protocols to ensure long-term sustainability and operational efficiency.

Studies on policy and regulatory frameworks, such as reports from the International Hydropower Association (IHA) and national energy authorities, emphasize the role of supportive policies in promoting decentralized energy solutions. This research aligns with recommendations to establish clear regulatory guidelines, streamline approval processes, and provide financial incentives to foster the expansion of picohydro installations worldwide.

Challenges Encountered During the Design and Analysis Process of Picohydro Power Plants

The design and analysis of picohydro power plants present several challenges that necessitate careful consideration and innovative solutions. Throughout the research process, various obstacles were encountered, ranging from technical complexities to socio-economic factors.

Each picohydro site presents unique characteristics in terms of water flow, head height, and environmental conditions, posing challenges for standardization in design and implementation. Detailed hydrological assessments and site surveys were conducted to gather accurate data on flow rates, head heights, and environmental impacts. This information guided customized design solutions tailored to each specific site, optimizing turbine selection, intake designs, and system configurations accordingly.

Selecting the most suitable turbine type and optimizing its efficiency across varying flow conditions required thorough analysis and iterative adjustments. Computational fluid dynamics (CFD) simulations and empirical data from pilot projects were utilized to model turbine performance under different operational scenarios. This approach facilitated the identification of optimal turbine designs and operational parameters, ensuring maximum energy extraction and system efficiency.

Integrating picohydro systems with existing infrastructure, such as grid connections or off-grid distribution networks, posed logistical and technical challenges. Collaborative partnerships with local utilities and community stakeholders were established to streamline integration processes. Customizable system configurations and modular designs were adopted to facilitate seamless integration with diverse energy grids and distribution networks, ensuring compatibility and reliability.

Gaining community support and fostering acceptance of picohydro projects required addressing local perceptions, socio-economic concerns, and cultural sensitivities. Extensive community consultations, participatory decision-making processes, and awareness campaigns were conducted to educate stakeholders about the benefits of picohydro systems. Tailored socio-economic assessments and capacity-building initiatives were implemented to empower local communities and ensure inclusive project development and management.

Minimizing environmental impacts, such as habitat disturbance and water quality degradation, posed significant regulatory and operational challenges. Comprehensive environmental impact assessments (EIAs) were conducted to evaluate potential ecological risks and identify mitigation measures. Innovative engineering solutions, such as fish-friendly turbine designs and erosion control structures, were implemented to mitigate adverse environmental effects and ensure compliance with environmental regulations and sustainability standards.

Building local capacity and ensuring sufficient technical expertise for the operation and maintenance of picohydro systems in remote and rural areas. Training programs and skill development workshops were organized for local technicians and operators to enhance their knowledge of system maintenance, troubleshooting, and emergency response protocols. Long-term partnerships with educational institutions and vocational training centers were fostered to sustainably transfer technical skills and promote local ownership of picohydro installations.

Achieving financial viability and ensuring the long-term sustainability of picohydro projects amid fluctuating funding sources and economic uncertainties. Financial modeling and feasibility assessments were conducted to evaluate project economics, assess return on investment (ROI), and identify potential revenue streams, such as energy sales or carbon credits. Partnerships with development finance institutions and private sector stakeholders were leveraged to secure financing, mitigate financial risks, and ensure the economic sustainability of picohydro initiatives.

Broader Implications of Picohydro Power Plant Findings

The findings from research on picohydro power plants carry profound implications for the field of renewable energy and rural electrification, offering insights into sustainable development, energy access, and environmental stewardship.

Picohydro power plants exemplify decentralized energy solutions that contribute to diversifying the energy mix and reducing dependency on centralized fossil fuel-based electricity generation. The findings underscore their role in promoting energy security and resilience, particularly in remote and off-grid areas where conventional grid infrastructure is economically unfeasible. Integrated with solar, wind, and biomass energy sources, picohydro systems contribute to hybrid renewable energy solutions. This integration enhances energy reliability and mitigates intermittency issues associated with standalone renewable technologies, supporting the transition towards sustainable and resilient energy systems.

Picohydro power plants significantly enhance energy access in rural and underserved communities, providing reliable electricity for households, schools, healthcare facilities, and small businesses. The findings demonstrate their transformative impact on socio-economic development by enabling productive activities, improving educational outcomes, and enhancing overall quality of life. Access to electricity from picohydro systems stimulates local economic development through increased agricultural productivity, expanded access to markets, and the emergence of new livelihood opportunities. Sustainable energy access fosters entrepreneurship and small-scale industries, driving economic growth and reducing poverty in rural areas.

Picohydro power plants offer a sustainable alternative to fossil fuel-based electricity generation, significantly reducing greenhouse gas emissions and mitigating climate change impacts. The findings highlight their role in promoting environmental sustainability through minimal land footprint, low operational emissions, and ecosystem-friendly design practices. By harnessing the renewable energy potential of flowing water, picohydro systems contribute to the conservation of natural resources and ecosystem integrity. The research emphasizes the importance of eco-friendly design features, such as fish-friendly turbines and sediment control measures, in preserving aquatic habitats and water quality.

The findings underscore the need for supportive policies and regulatory frameworks that prioritize decentralized energy solutions, including picohydro power. Policy incentives, such as feed-in tariffs, tax incentives, and streamlined permitting processes, are crucial for attracting investment, accelerating project deployment, and scaling up picohydro installations globally. Capacity-building initiatives and knowledge-sharing platforms are essential for empowering local communities, building technical expertise, and promoting sustainable management of picohydro installations. Educational programs, vocational training, and partnerships with academic institutions facilitate skills development and foster local ownership of renewable energy projects.

Conclusion

This research has delved deeply into the design, efficiency, and socio-economic implications of picohydro power plants, focusing on their role in sustainable energy generation and rural electrification. Through a comprehensive analysis of turbine selection, system optimization, and environmental considerations, several key findings have emerged. Firstly, optimal turbine selection and design customization are crucial for maximizing energy extraction efficiency from varying water flow conditions. This underscores the importance of tailored engineering solutions to enhance overall system performance. Secondly, picohydro systems have demonstrated significant potential in enhancing energy access and fostering economic development in remote and underserved communities. By providing reliable electricity for households, schools, and small enterprises, these systems contribute to improving living standards and promoting socio-economic empowerment. Environmental sustainability has also been a central focus, with findings emphasizing the importance of eco-friendly design practices and mitigation strategies to minimize ecological impacts on aquatic habitats and water quality. The broader implications of this research extend to policy recommendations that support decentralized renewable energy solutions. Effective policy frameworks, coupled with technological innovations and community engagement, are essential for scaling up picohydro installations and achieving sustainable development goals. By harnessing the natural energy potential of flowing water, these systems not only contribute to mitigating climate change but also empower communities and promote inclusive growth worldwide.

Reference

Albert, M. J. (2021). The climate crisis, renewable energy, and the changing landscape of global energy politics. *Alternatives*, *46*(3), 89–98.

Blackmore, M. (2013). *Small Hydropower Research and Development Technology Project*. near Space Systems, Inc.

Chang, X., Wei, K., Ye, L., Ding, J., & Liu, Q. (2021). Optimization and feasibility analysis of pico-hydro generation system used in small agricultural pipe network. *Journal of Physics: Conference Series*, *2030*(1), 12005.

Chehouri, A., Younes, R., Ilinca, A., & Perron, J. (2015). Review of performance optimization techniques applied to wind turbines. *Applied Energy*, *142*, 361–388.

Davie, T. (2019). *Fundamentals of hydrology*. Routledge.

Desai, A., Mukhopadhyay, I., & Ray, A. (2014). Theoretical analysis of a Pico-hydro power system for energy generation in rural or isolated area. *2014 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, 1–4.

Dincer, I., & Acar, C. (2015). A review on clean energy solutions for better sustainability. *International Journal of Energy Research*, *39*(5), 585–606.

Edeoja, A. O., Ibrahim, J. S., & Kucha, E. I. (2015). Conceptual design of a simplified decentralized Pico hydropower with provision for recycling water. *Journal of Multidisciplinary Engineering Science and Technology*, *2*(2), 22–34.

Edeoja, A. O., Ibrahim, J. S., & Kucha, E. I. (2016). Investigation of the Effect of Penstock Configuration on the Performance of a Simplified Pico-hydro System. *British Journal of Applied Science & Technology*, *14*(5), 1.

Gable, G. G. (1994). Integrating case study and survey research methods: an example in information systems. *European Journal of Information Systems*, *3*, 112–126.

Haines, A., Smith, K. R., Anderson, D., Epstein, P. R., McMichael, A. J., Roberts, I., Wilkinson, P., Woodcock, J., & Woods, J. (2007). Policies for accelerating access to clean energy, improving health, advancing development, and mitigating climate change. *The Lancet*, *370*(9594), 1264–1281.

Kamran, M. (2021). Hydro energy. *Renewable Energy Conversion Systems*, 193–219.

Kaunda, C. S., Kimambo, C. Z., & Nielsen, T. K. (2012). Potential of small-scale hydropower for electricity generation in Sub-Saharan Africa. *ISRN Renewable Energy*.

Kaunda, C. S., Kimambo, C. Z., & Nielsen, T. K. (2014). A technical discussion on microhydropower technology and its turbines. *Renewable and Sustainable Energy Reviews*, *35*, 445–459.

Kishore, T. S., Patro, E. R., Harish, V., & Haghighi, A. T. (2021). A comprehensive study on the recent progress and trends in development of small hydropower projects. *Energies*, *14*(10), 2882.

Lahimer, A. A., Alghoul, M. A., Sopian, K., Amin, N., Asim, N., & Fadhel, M. I. (2012). Research and development aspects of pico-hydro power. *Renewable and Sustainable Energy Reviews*, *16*(8), 5861–5878.

Muchira, M. J. (2011). Performance of a modified vehicle drive system in generating hydropower. *MSc. Renewable Energy Technology Thesis, Kenyatta University, Kenya*, *44*.

Murray, C. J. L., Ezzati, M., Flaxman, A. D., Lim, S., Lozano, R., Michaud, C., Naghavi, M., Salomon, J. A., Shibuya, K., & Vos, T. (2012). GBD 2010: design, definitions, and metrics. *The Lancet*, *380*(9859), 2063–2066.

Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*, *143*, 172–196.

Pachauri, S., Brew-Hammond, A., Barnes, D. F., Bouille, D. H., Gitonga, S., Modi, V., Prasad, G., Rath, A., & Zerrifi, H. (2012). *Energy access for development*.

Pérez-Sánchez, M., Sánchez-Romero, F. J., Ramos, H. M., & López-Jiménez, P. A. (2017). Energy recovery in existing water networks: Towards greater sustainability. *Water*, *9*(2), 97.

Pourmousavi, S. A., Nehrir, M. H., Colson, C. M., & Wang, C. (2010). Real-time energy management of a stand-alone hybrid wind-microturbine energy system using particle swarm optimization. *IEEE Transactions on Sustainable Energy*, *1*(3), 193–201.

Powell, D., Ebrahimi, A., Nourbakhsh, S., Meshkahaldini, M., & Bilton, A. M. (2018). Design of pico-hydro turbine generator systems for self-powered electrochemical water disinfection devices. *Renewable Energy*, *123*, 590–602.

Sachdev, H. S., Akella, A. K., & Kumar, N. (2015). Analysis and evaluation of small hydropower plants: A bibliographical survey. *Renewable and Sustainable Energy Reviews*, *51*, 1013–1022.

Sangal, S., Garg, A., & Kumar, D. (2013). Review of optimal selection of turbines for hydroelectric projects. *International Journal of Emerging Technology and Advanced Engineering*, *3*(3), 424–430.

Sturdivant, R., Yeh, J., Stambaugh, M., Zahnd, A., & Chong, E. K. P. (2017). Pico-hydro electric power in the nepal himalayas. *2017 Ninth Annual IEEE Green Technologies Conference (GreenTech)*, 232–237.

Williamson, S. J., Lubitz, W. D., Williams, A. A., Booker, J. D., & Butchers, J. P. (2019). Challenges facing the implementation of pico-hydropower technologies. *Journal of Sustainability Research*, *4*(3).