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TOPICAL REVIEW

Eco-Friendly Energy From Flowing Water: A Review of Floating Waterwheel Power Generation

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ABSTRACT This review explores the potential of floating waterwheel power generation systems as a sustainable source of energy. With increasing concerns about environmental degradation and the need for renewable energy sources, the utilization of flowing water for power generation presents an attractive solution. By analyzing existing literature and case studies, this review assesses the feasibility and effectiveness of floating waterwheel systems in harnessing energy from rivers and streams. Key metrics, including the total potential of floating hydro generation systems and their contribution to renewable energy, are evaluated to provide insights into the scalability and impact of this technology. Furthermore, the review identifies the most viable types of generating systems and highlights the environmental benefits they offer. This paper outlines the significant potential of floating hydro generation systems, with an estimated contribution of up to 10% of global renewable energy production. Among these systems, tidal barrage technology stands out as the most viable option, offering predictability and high energy density. By harnessing the power of moving rivers and tides, this technology addresses the pressing demand for clean energy while minimizing environmental impact compared to traditional dams. By addressing these aspects, this study aims to contribute to the advancement of eco-friendly energy solutions and provide valuable insights for policymakers, researchers, and industry professionals working in the field of renewable energy.

INDEX TERMS Pico hydro power plants, small scale hydropower, floating structured systems, sustainable energy generation, renewable energy solutions, environmental impact, energy self-sufficiency, hydropower innovation, grid independence.

I. INTRODUCTION

The utilization of hydropower, as an ancient and enduring source of renewable energy, holds a unique place in the annals of human history [1]. For over two millennia, humanity has harnessed the power of flowing water to fuel various applications, from mechanical processes to electricity generation [2]. Major hydroelectric projects face various social, political, and technical challenges. Even though the government has made significant efforts, concerns about the Kalabagh Dam from the Sindh and North-West Frontier Province (NWFP) regions persist [3]. The development of barrages and dams

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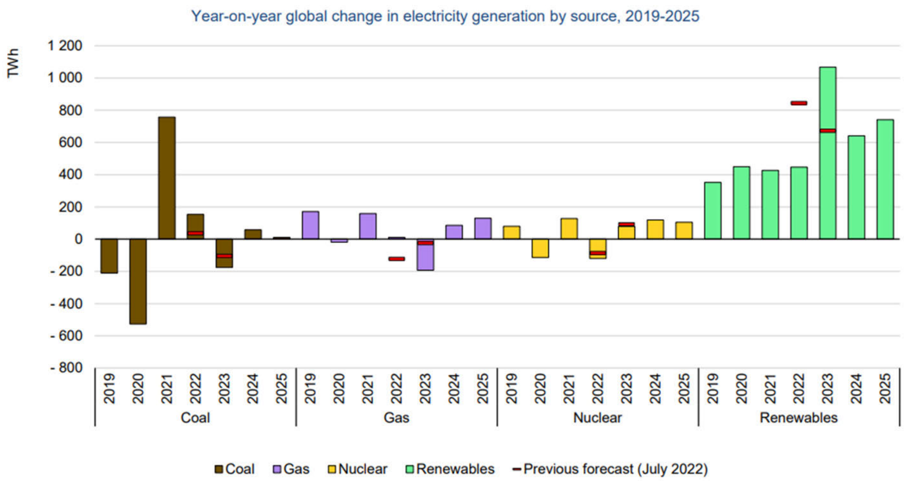


FIGURE 1. Growth in RE will reduce the use of fossil fuels to generate electricity [6].

upstream of the Indus River has negatively impacted the Indus delta. The promises of affordable hydroelectric power from these large dams, when viewed through the lens of sustainable development, may not be reliable for two primary reasons. First, there is a growing demand to incorporate the costs associated with social displacement and environmental degradation into the initial capital expenses of such projects [4], [5].

The International Energy Agency's (IEA) latest report brings promising news for the renewable energy sector. The global share of renewable in the power generation mix is expected to climb from 29% to 35% by 2025 illustrated in Figure 1. This growth will come at the expense of coal and gas-fired generation, leading to a decrease in global power-sector CO2 emissions. Notably, China is projected to be a major driver of this shift, contributing nearly half of the additional renewable generation, followed by the European Union with 15%. The rise in renewable can be attributed to increased government investments in sustainable energy as part of economic recovery strategies, underscoring the sector's pivotal role in reducing fossil fuel-based electricity generation and curbing carbon emissions [6], [7].

The primary concern in dealing with these massive projects is securing the necessary funds. Obtaining financial support from international donors for such endeavors is challenging, primarily because these donors are more committed to promoting investments in privately-owned thermal power plants [8]. In [9] provides valuable insights into the design and efficiency of portable hydro power plants. By utilizing data collected through extensive surveys and quantitative analysis, the study determines key parameters such as water flow distribution and turbine thread design. The calculated efficiency of 59.6% demonstrates the potential for significant power generation, with theoretical power reaching 1114.42 Watts. These findings underscore the feasibility and effectiveness of Archimedean screw turbines in portable hydro power applications. In [10] the focus is on addressing small-scale electricity needs while promoting environmental sustainability. By combining solar and micro hydro energy sources, the study introduces a versatile and portable power solution suitable for diverse environments. Tested in real-world conditions, the hybrid power plant with a maximum capacity of 1100 watts demonstrates promising performance, particularly in agricultural settings where electricity is essential for pest control and irrigation. In [11] presents a comprehensive analysis of design methodologies for run-of-river hydropower projects. Emphasizing the importance of appropriate design models, the study evaluates various factors influencing energy production and project cost. By highlighting the specificity of each model and proposing efficient utilization methods, the review serves as a valuable guide for engineers and researchers involved in hydropower project planning and design. In [12] researchers focus on maximizing the efficiency of floating hydroelectric power plants through theoretical analysis and computational fluid dynamics simulations. By analyzing different floating pontoon designs, the study identifies optimal configurations for enhanced energy generation. The findings contribute to the ongoing efforts to improve the performance and sustainability of renewable energy systems, paving the way for future advancements in floating hydroelectric power technology.

The public's image of Small Hydropower Plants (SHPs) as sustainable energy sources has shifted in recent decades [13], [14]. Investors are drawn to SHPs due to the reduced bureaucratic requirements for licensing and the possibility of decentralized operation and management. These facilities have sparked a great deal of interest in the development of these hydroelectric projects, especially Run-of-River (RoR) plans [15], [16].The greatest option for supplying decentralized power in distant highland communities with a nearby naturally occurring stream of water (perennial or seasonal) is determined to be RoR MHP (Micro Hydro Power), which is thought to be a renewable power source [17], [18]. Micro Hydel Power has several benefits, including as quick and

TABLE 1. Types of small hydropower plants [23].

Category	Installed Capacity
Small Hydro Power Plants	Less than 25 MW
Mini Hydro Power Plants	100 kW to 1 MW
Micro Hydro Power Plants	5 kW to 100 kW
Pico Hydro Power Plants	Less than 5 kW

dependable power dispatch, effective regulation, and the option to operate in standalone or grid-connected mode. These systems have a number of drawbacks, such as high installation capital costs, seasonal variations in power generation, and plant underperformance brought on by complicated sites [19]. According to [20], large growth in the use of small hydropower are anticipated in Brazil and India, with over 30% of China's districts currently significantly dependent on this type of energy. To generate hydropower on a small scale, different kinds of water wheels, either fixed or floating, have been constructed. The effectiveness of the water wheel to generate hydropower has been shown in earlier research to be strongly influenced by a few design factors, including the profile of the ridge, the number of blades, and the immersed radius ratio [21].

Furthermore, even if the government manages to secure the funding for these projects, the expenses related to compensating and resettling affected communities are substantial. For instance, the government plans to allocate Rs 2.025 billion to address the resettlement challenges associated with the Kalabagh Dam by building 20 model villages and 27 extended settlements [22]. Globally, large-scale hydroelectric power projects are not typically classified as renewable energy options because of their adverse effects on the local environment and the displacement of communities due to flooding. Table 1 shows the different categories of small hydro according to their installed capacity.

There is compelling evidence to suggest that such large schemes release greenhouse gases, often on par with fossil fuel power plants, due to the decomposition of submerged biomass. In contrast, small-scale hydropower facilities have gained popularity, particularly in hilly regions where natural and manageable waterfalls are abundant [23]. These smaller hydropower plants are environmentally friendly, have shorter development periods, and have garnered international attention in both developed and developing nations as a means to enhance energy production. Small hydropower projects offer numerous advantages, especially for rural areas in developing countries. Hydropower, characterized by its sustainability, cost-effectiveness, and environmental friendliness, has consistently contributed to meeting energy demands while simultaneously mitigating the consequences of fossil fuel consumption. In this context, we embark on a journey to explore a contemporary facet of hydropower technology the floating structured pico hydro power plant. These innovative systems offer an efficient and eco-friendly means of capturing hydropower from small canals, rivers, and streams, and they stand as a testament to the enduring relevance of this age-old energy source [24].

The in-depth theoretical analysis of the water wheel design reveals its foundation in hydrodynamics, aiming to optimize efficiency and performance. By considering the flow characteristics and interaction with the wheel blades, the design minimizes energy losses and maximizes power generation. The balance between kinetic and potential energy is carefully addressed, allowing the wheel to extract greater power from the flowing water. Smooth flow is achieved through streamlined inlet and outlet configurations, reducing turbulence and energy dissipation. The design also prioritizes ecological sustainability by avoiding water extraction from the river. The analysis explores the relationship between water volume handled and efficiency, facilitating increased capacity and improved power output. Theoretical modeling and simulations inform design parameters, optimizing blade shape, spacing, and rotational speed. Furthermore, the analysis assesses the economic viability, accounting for installation costs, maintenance, and expected lifespan, providing insights into long-term financial benefits.

However, we want to emphasize the fact that Pico hydropower plants are typically small-scale hydroelectric systems that can be connected to a local grid or used as standalone systems to power remote areas. The decision to connect them to the grid depends on factors such as proximity to existing infrastructure, regulatory requirements, and the community's energy needs. Some Pico hydro systems are designed to operate independently to provide off-grid power solutions in rural or isolated areas. Noteworthy to mention that Pico hydropower plants are typically small-scale hydroelectric systems and can be connected to a local grid or used as standalone systems to power remote areas. The decision to connect them to the grid depends on factors such as proximity to existing infrastructure, regulatory requirements, and the community's energy needs. Some Pico hydro systems are designed to operate independently to provide off-grid power solutions in rural or isolated areas.

A. THE SIGNIFICANCE OF HYDROPOWER AS A RENEWABLE ENERGY SOURCE

Hydropower, as a renewable energy source, occupies a prominent position within the global energy landscape. It represents a resource that is both replenishable and sustainable, derived from the perpetual movement of water driven by Earth's natural processes [25]. The use of hydropower aligns perfectly with the broader transition towards cleaner, more sustainable energy sources that are essential for mitigating the challenges posed by climate change, dwindling fossil fuel reserves, and environmental degradation [26]. Notably, hydropower has minimal greenhouse gas emissions and serves as a critical component of the energy mix in many nations. In the global electricity generation landscape, renewable energy sources play a significant role, constituting a considerable share of 2587.6 gigawatts. Hydropower stands as the largest contributor to electricity production as depicted in Figure 2. Moreover, the combined forces of solar and wind energy make up 50% of the total electricity share. Meanwhile, geothermal,

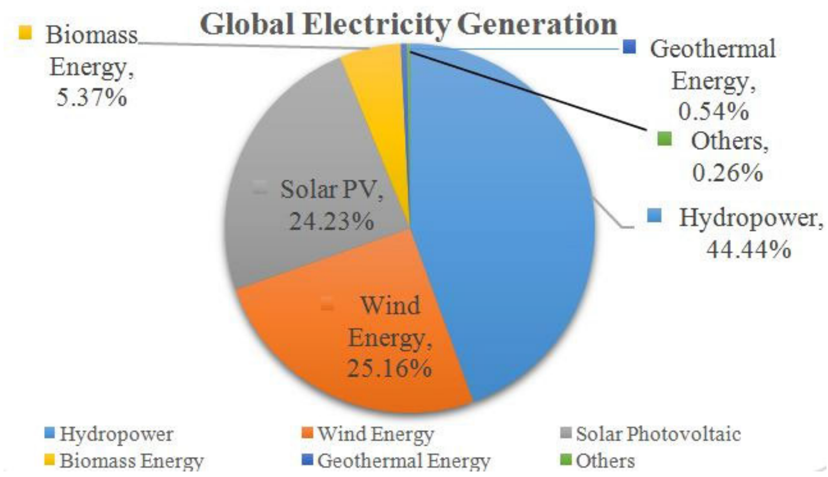


FIGURE 2. Global electricity generation breakdown by renewable sources [27].

TABLE 2. Comparisons between pico hydro vs. other energy sources.

Energy Source	Advantages	Limitations
Pico Hydro	- Suitable for remote areas	- Limited power output
	- Low cost installation and maintenance	- Dependent on consistent water flow
	- Minimal environmental impact	- Limited scalability
Micro Hydro	- Higher power output compared to pico hydro	- Requires moderate to high water flow
	- Relatively low environmental impact	- Initial investment can be significant
	- Can be integrated with existing water infrastructure for cost savings	- Environmental and regulatory hurdles
Small-scale Dam	- Higher power output than micro hydro	- Significant environmental impact
	- Provides flood control and water storage	- Displacement of communities and ecosystems
	- Long lifespan and reliability	- Expensive construction and maintenance costs

ocean, and biomass-based power plants contribute slightly over 6%, highlighting the diversification of renewable energy technologies in the global energy mix. This shift towards cleaner and more sustainable power sources is essential in the fight against climate change and reducing our reliance on fossil fuels [27].The historical significance of hydropower is deeply rooted in the development of early human civilizations. Ancient societies, including the Greeks, Romans, and Egyptians, harnessed the power of water wheels for tasks like milling grain and sawing wood.

The earliest documented use of hydropower can be traced to ancient China, where water wheels were employed as far back as the 1st century AD. The ingenious design and use of water wheels marked a paradigm shift in harnessing the kinetic energy of flowing water, enabling numerous technological advancements throughout history [28].

Comparison between Pico hydro vs. other energy sources has been presented in Table2 [29].

B. SMALL-SCALE HYDROPOWER AND ITS UNTAPPED POTENTIAL

In the contemporary energy landscape, small-scale hydropower assumes a significant role, as it targets energy generation on a more localized scale, in contrast to large-scale hydroelectric plants. Small-scale hydropower systems are often defined by their capacity, with a focus on installations with a generating capacity below 25MW, rendering them ideal for distributed energy generation [30].

It is imperative to underscore that such small-scale hydropower projects remain an untapped and underutilized resource, especially in regions with abundant water resources. A compelling example of this untapped potential is the case of Pakistan. In Pakistan, the recoverable hydropower potential is estimated to be approximately 40,000 megawatts, a vast energy reserve that remains largely unexplored [31], [32]. This lack of development stems from a combination of economic, social, and political constraints that have hindered the realization of this immense energy resource. Despite the existence of natural locations suitable for large-scale hydropower projects, these opportunities have remained on hold for a protracted period, perpetuating the energy challenges faced by the nation. Notably, over 70% of Pakistan's population resides in rural areas, often located far from the national grid. Given the current economic realities, connecting these remote regions to the national grid is a challenging and economically unviable endeavor [32].

In such circumstances, standalone power systems that harness small, pico, or micro hydro turbines offer an economical and pragmatic solution. These localized systems can tap into available water resources in the form of rivers or streams, providing sustainable energy sources for these often overlooked communities [33]. The design and fabrication of hydropower turbines can be complex and costly, primarily due to the specialized knowledge, skills, and fabrication facilities required. This inherent complexity has directed attention toward run-of-river generating units, including waterwheels, as an alternative and simplified solution. Waterwheels are particularly appealing because they do not necessitate the construction of dams, a requirement often associated with traditional turbines. The resurgence of waterwheel technology has been observed in technologically advanced and developing countries, as they offer a low-cost approach to micro and pico power generation [34].

C. SCOPE OF THIS REVIEW

This review paper examines the potential of floating structured pico hydropower plants compared to traditional hydropower, focusing on efficiency, practicality, and adaptability. It explores their role in capturing untapped hydropower resources, reducing carbon emissions, and contributing to cost-effective energy generation for sustainable landscapes. As the world transitions to greener energy sources, these plants offer promising solutions for addressing global energy challenges. Subsequent sections will provide a detailed analysis of their operational efficiency, comparative advantages, and impact on energy grids, offering valuable insights for stakeholders and policymakers.

D. AIM AND OBJECTIVES

This review paper aims to comprehensively explore the potential of floating structured pico hydropower plants in the context of small-scale hydropower. This exploration is driven by the following main objectives:

1. **Evaluation of Floating Waterwheel Power Generators:** The primary objective of this research is to evaluate the feasibility and effectiveness of floating waterwheel power generators as a renewable energy solution. This includes assessing their design, functionality, and potential applications in small-scale hydropower projects.
2. **Assessment of Environmental and Economic Impacts:** This involves analyzing their ecological footprint, cost-effectiveness, and contributions to sustainable energy production, as well as their potential role in rural electrification and economic development.
3. **Investigation of Experimental Research and Efficiency Optimization:** Another objective is to investigate experimental research and efficiency optimization techniques to enhance the performance, reliability, and cost-effectiveness of floating waterwheel power generators. This includes exploring various aspects such as performance testing, design optimization, and environmental impact assessment to maximize energy output while minimizing environmental disruption and operational costs.

II. HYDROPOWER AS A RENEWABLE ENERGY SOURCE

Renewable energy sources are classified based on their ability to naturally replenish themselves and their minimal impact on the environment. These classifications include solar energy, wind energy, hydropower, biomass energy, and geothermal energy [35], [36]. Hydropower plays a significant role in the renewable energy landscape. It is derived from the energy of flowing or falling water, which is harnessed to drive turbines and generate electricity [37]. One of the key advantages of hydropower is its abundance as a resource. Water is a renewable source that is naturally replenished through the water cycle, ensuring a consistent and reliable energy supply [38]. Hydropower offers several benefits in the renewable energy sector. Firstly, it has a high energy potential. Even small quantities of water can generate large amounts of electricity, making it a highly efficient energy source. Hydropower plants are capable of providing a stable and continuous power supply, making them suitable for meeting the base load demand of electricity grids [39]. This stability and reliability contribute to the overall energy security of a region or country. Another advantage of hydropower is its ability to act as an energy storage system. Hydropower reservoirs can store excess electricity generated during periods of low demand and release it during times of peak demand [40]. This energy storage capability enhances grid stability and allows for better integration with other renewable energy sources that have intermittent generation, such as solar and wind. Hydropower thus plays a crucial role in balancing the supply and demand of electricity in a sustainable manner.

Small hydropower offers several notable advantages over other energy sources like wind, wave, and solar power. These advantages include:

- **High Efficiency:** Hydrokinetic power systems can achieve reasonable conversion efficiency, ranging from 20% to 30%, making them a viable option for harnessing water energy.
- **High Capacity Factor:** They typically maintain a high capacity factor, exceeding 50%, in contrast to the lower capacity factors of less than 10% for solar and around 30% for wind.
- **Predictability:** Small hydropower's predictability is closely tied to annual rainfall patterns.
- **Stable Output:**The output power changes gradually from day to day rather than fluctuating rapidly from minute to minute.
- **Demand Correlation:** It has a strong correlation with energy demand.
- **Continuous Generation:** Small hydropower systems operate 24 hours a day, including at night.
- **Longevity:** This technology is known for its durability, with well-engineered systems capable of functioning for 50 years or more. It means that the technology is known for its ability to remain operational and functional for an extended period without significant degradation or failure. In this case, it suggests that well-engineered systems utilizing this technology can operate effectively for 50 years or more.
- **Environmental Friendliness:** Properly designed small hydropower schemes are environmentally benign, often referred to as "run-of-river," meaning they involve

TABLE 3. Comparison of kinetic and potential hydraulic power.

Kinetic Hydraulic Power	Potential Hydraulic Power
The energy of water in motion, such as currents, tides, or waves.	The energy of water at rest, such as in reservoirs, dams, or elevated tanks.
Uses turbines or rotors that are directly driven by the water flow.	Uses turbines or pumps that are driven by the water pressure or head.
Lower conversion efficiencies, typically around 20-30%.	Higher conversion efficiencies, typically around 80-90%.
Lower power density, usually less than 1 kW/m2.	Higher power density, usually more than 10kW/m2.
More variable and intermittent, depending on the natural conditions.	More controllable and reliable, depending on the human operation.

TABLE 4. Potential for micro, mini, and small hydropower in pakistan [44].

Province	No. of Potential Locations	Potential Range (MW)	Total potential (MW)	Remarks
North Western Frontier Province	77	0.02~32	426.41	Small Dams, Natural Falls
Punjab	306	0.02~40	349.6559	Canal Falls
Northern areas	136	0.1~38	814	Natural Falls
Sindh	10	0.5~40	98.05	Canal Falls
Balochistan	NA	NA	0.55	NA
Azad Jammu & Kashmir	24	0.2~40	177.00	Natural Falls
Total	546	0.02~40	1865.8159	

minimal impoundment, typically using existing weirs and storing little to no water [41].

In terms of environmental benefits, using water as an energy source offers numerous advantages. Hydropower plants produce negligible greenhouse gas emissions during operation, making them an environmentally friendly alternative to fossil fuel-based power generation [42]. By reducing the reliance on fossil fuels, hydropower significantly contributes to the reduction of carbon dioxide and other greenhouse gases, thereby mitigating climate change. Hydropower eliminates or minimizes air pollutants associated with the combustion of fossil fuels. This leads to improved air quality and subsequent benefits for human health. The use of water as an energy source also promotes water conservation [43]. Hydropower plants can regulate water flow, which contributes to flood control, water supply management, and irrigation. By optimizing water resources, hydropower helps in preserving this valuable natural resource. Table 3 compares the main characteristics and differences between kinetic and potential hydraulic power, which are two forms of renewable energy derived from water.

In Pakistan, small hydropower is classified with an upper capacity limit of up to 50 MW. Table 4 provides a list of potential small hydropower sites organized by province. If these sites are developed, they have the potential to contribute an additional 1865 MW of power generation capacity [44].

In terms of biodiversity and ecosystem preservation, properly designed and managed hydropower projects can minimize adverse impacts on aquatic ecosystems. Measures such as fish ladders or bypass systems can facilitate fish migration, maintain river habitats, and support biodiversity [45]. Careful planning and environmental assessments are crucial to minimize any potential negative impacts on ecosystems and maximize the positive contributions of hydropower to the environment. Hydropower is a vital component of the renewable energy landscape. Its classification as a renewable energy source stems from its ability to harness the energy of flowing or falling water. Hydropower provides a stable and reliable energy supply, contributes to grid stability through energy storage, and integrates well with other renewable sources. From an environmental perspective, it offers significant advantages such as lower greenhouse gas emissions and better air quality, water conservation, and ecosystem preservation. However, it is critical to guarantee that hydropower projects are completed are carefully planned and managed to minimize any potential adverse impacts on communities and ecosystems [46].

A. INTEGRATION OF OPTIMIZATION ALGORITHMS AND DYNAMICAL ANALYSIS

Designing efficient floating waterwheel systems involves a multidimensional approach that integrates optimization algorithms and dynamical analysis. Optimization algorithms play a crucial role in enhancing performance, reliability, and cost-effectiveness [47]. While specific algorithms may vary, common approaches include multi-objective optimization, network analysis-supported design, mathematical modeling, and design for assembly, morphology analysis, and real-time dynamic layout optimization [48]. These techniques enable researchers to identify optimal design parameters and trade-off solutions, streamline assembly processes, and explore different design alternatives systematically [49]. Dynamical analysis complements optimization efforts by studying system behavior over time and considering dynamic factors such as water flow variations, turbulence, and mechanical interactions [50]. Through dynamical simulations, researchers gain insights into transient behavior, rotor dynamics, control strategies, and hydrodynamic effects. Understanding these intricacies allows for the refinement of design parameters, optimization of control strategies, and improvement of system stability [51]. By integrating optimization algorithms and dynamical analysis, designers can develop floating waterwheel systems that are not only efficient but also robust and adaptable to changing environmental conditions [52].

III. FLOATING WATERWHEEL POWER GENERATORS

The concept of floating waterwheel power generators described in the document involves the development of a standalone power generation system that utilizes the flow

FIGURE 3. Shows the concept of floating waterwheel power generators [55].

of water in rivers and canals [53]. The system consists of a floating structure equipped with a water wheel, which is driven by the flowing water. The rotation of the water wheel generates power that can be used for various applications, such as village electrification, agriculture water pumping, and bridge street lights. The physical structure of the system is designed using non-corrosive and unbreakable materials like mild steel and fiberglass [54]. The water wheel is specially designed with blades that rotate in the direction of the water flow, ensuring continuous power generation. The system operates independently without the need for external electric grid power. The generated power can be used directly or stored in batteries for later use. One of the main advantages of waterwheel power generators over traditional hydropower turbines is their portability and flexibility as depicted in Figure 3.

The floating nature of the system allows it to be easily anchored and unanchored in different water bodies, such as canals and rivers. This mobility enables the system to be deployed where needed, offering greater accessibility to remote areas or locations with varying water flow conditions [56]. Waterwheels are less expensive to install and maintain than standard hydropower turbines. The system described in the document does not require permanent installations or civil foundations, which can be expensive and time-consuming. This makes floating waterwheel power generators a cost-effective option, particularly in areas where constructing dams or large-scale hydroelectric plants may not be feasible. Another advantage of waterwheels is their environmental friendliness. The system operates without causing pollution and utilizes renewable energy from flowing water [37], [57]. It does not require the construction of dams or impoundments, minimizing the potential negative impacts on ecosystems and aquatic habitats. This makes waterwheel power generators a sustainable and green energy solution. The floating waterwheel power generators described in the document offer a high level of efficiency. The design incorporates aerodynamically designed floats and utilizes the force of flowing water to drive the water wheel, even at lower flow rates. The system includes a linear power generator and can harness the energy from the flowing water with relatively low maintenance requirements [58]. This combination of efficiency and low maintenance contributes to the long-term viability and reliability of the system. Floating waterwheel power generators are innovative systems that harness the power of flowing water in rivers and canals. They offer advantages such as portability, cost-effectiveness, environmental friendliness, and high efficiency compared to traditional hydropower turbines [59]. These systems have the potential to provide sustainable and accessible power generation for various applications, particularly in areas with abundant water resources as shown in Table 5.

TABLE 5. Advantages of waterwheels over traditional hydropower turbines.

Advantages	Description
Portability and Flexibility	Waterwheels can be easily anchored and unanchored in different water bodies, allowing deployment in various locations.
	This makes them more accessible, especially in remote areas or places with variable water flow conditions.
Lower Installation and Maintenance Costs	Waterwheels do not require permanent installations or civil foundations, reducing overall installation and maintenance costs.
	This makes them a cost-effective option, particularly in areas where constructing dams or large-scale hydro plants is not feasible.
Environmental Friendliness	Waterwheels operate without causing pollution and utilize renewable energy from flowing water.
	They do not require the construction of dams or impoundments, minimizing negative impacts on ecosystems and aquatic habitats.
High Efficiency and Low Maintenance	Waterwheel designs incorporate aerodynamics and utilize the force of flowing water efficiently, even at lower flow rates.
	They typically have relatively low maintenance requirements, contributing to their long-term viability and reliability.

A. CASE STUDY 1

The case study focuses on the design, modeling, and construction of an undershot floating waterwheel for electricity production in Pakistan. The objective of this study was to develop a sustainable and cost-effective solution for power generation in rural areas where connecting to the national grid is not feasible due to economic constraints. The researchers performed analytical modeling and simulation to determine the best design parameters for the waterwheel. They found that the water flow velocity played a significant role in determining the output power. With high flow velocity streams available, they were able to reduce the wheel's radius and width considerably [60]. Based on their simulations, the researchers obtained design estimates for a 1 kW power-generating waterwheel with a 1 m radius, and 10 blades, each having a width of 1.75 m and a height of 0.55 m. These parameters in Table 5 were found to be capable of generating the desired power from a stream flow velocity of 1.5 m/s. To validate their findings, a prototype of the undershot floating waterwheel was fabricated using lightweight materials such as fiberglass and mild steel square tubes. A DC generator was coupled with the output shaft of the waterwheel for electrical power generation. The prototype illustrated in Figure 4 successfully generated 0.6 kW of power at its highest

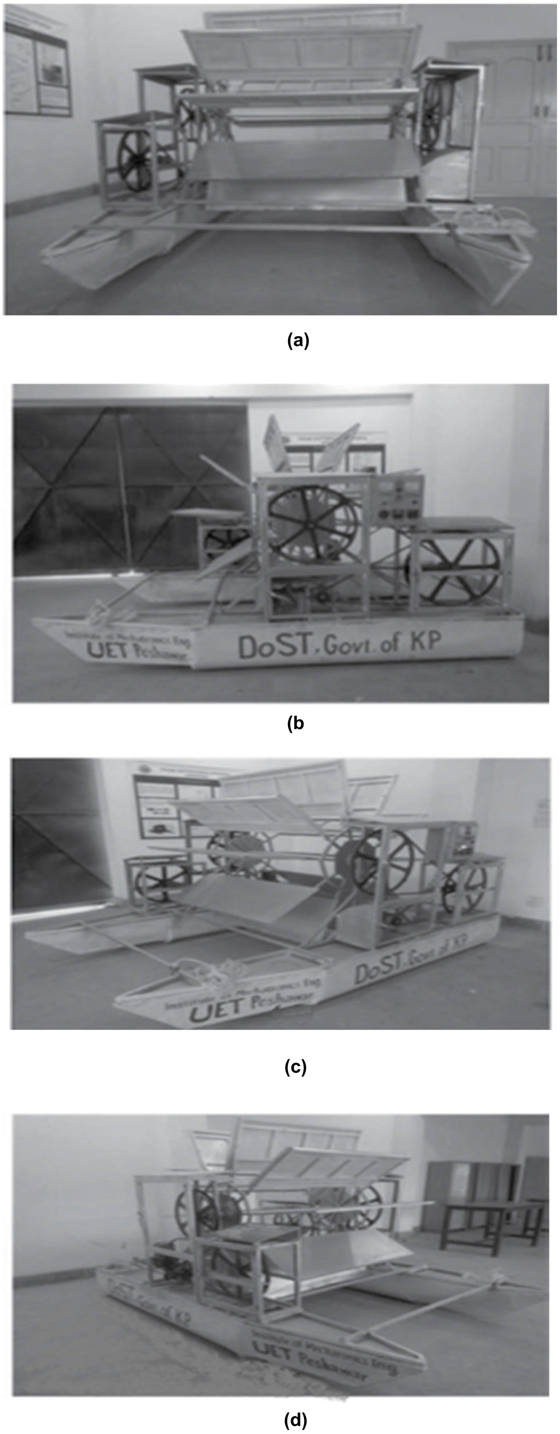


FIGURE 4. **Fabrication of optimized prototype floating waterwheel: (a) Floating waterwheel front view, (b) side view, (c) right isomeric view, (d) left isomeric view [60].**

rate from a 1.2 m/s water stream in an irrigation channel as shown in Table 6. The potential of utilizing waterwheels as a renewable energy source in Pakistan is particularly in rural areas where small-scale hydropower systems are economically viable.

Unlike traditional hydropower turbines that require dams, waterwheels can generate power from running water in rivers or streams, making them a suitable option for decentralized power generation. Decentralized pico-hydropower offers a sustainable solution for rural electrification, utilizing nearby streams or rivers to provide electricity to off-grid communities. Reducing reliance on fossil fuels and biomass not only enhances energy access but also improves both the quality of life and the environment in rural areas.

TABLE 6. **Summary of design aspects and key findings.**

Design Aspect	Key Findings
Design Objective	Develop a sustainable and cost-effective solution for power generation in rural areas of Pakistan where connecting to the national grid is not feasible due to economic constraints
System Design and Modeling	Analytical modeling and simulation were used to determine the best design parameters for the undershot floating waterwheel
Waterwheel Parameters	The radius of wheel: 1 m, Depth of blades: 0.55 m, Width of blades: 1.75 m, Number of blades: 10
Floats Dimensions	Length: 3 m, Width: 0.36 m, Height: 0.36 m
Generator Pulleys Dimensions	Big pulley diameter: 0.6 m, Small pulley diameter: 0.05 m, Speed ratio: 12
Pump Pulleys Dimensions	Big pulley diameter: 0.5 m, Small pulley diameter: 0.05 m, Speed ratio: 10
Electric Generator Specifications	Operating voltage: 12 V, Maximum current: 0.8 A
Pump Specifications	Maximum suction head: 8 m, Maximum delivery head: 40 m, Maximum discharge: 0.5 lit/s, Power consumption: 0.37 kW
Battery Specifications	Operating voltage: 12 V, Maximum current: 0.6 A
Waterwheel Overall Size	Length: 3 m, Width: 2.06 m, Height: 2.08 m
Power Output	The prototype generated 0.6 kW of power at its highest rate from a 1.2 m/s water stream in an irrigation channel

The environmental friendliness of waterwheels and their contribution is to reduce carbon dioxide emissions. With Pakistan having an estimated hydropower potential of approximately 40,000 MW, there is a significant opportunity to harness renewable energy from water resources. The case study underscores the importance of analytical modeling and simulation in optimizing the design parameters of the waterwheel. By accurately estimating the parameters, researchers can develop efficient and cost-effective power generation systems. The floating waterwheel power generator system in Pakistan demonstrates the feasibility and potential of utilizing this technology for sustainable and decentralized power generation. It serves as a valuable example for other countries facing similar challenges in providing electricity to remote and rural areas.

B. CASE STUDY 2

The case study focuses on a floating waterwheel power generator system that has been developed for various applications such as village electrification, agriculture water pumping, and bridge street lights. The system is designed to harness the power of flowing water in rivers and canals, making

TABLE 7. Summary of design aspects and key findings.

Design Aspect	Key Findings
Design Objective	Develop a floating waterwheel power generator system for village electrification, agriculture water pumping, and bridge street lights
System Applications	Village electrification, agriculture water pumping, and bridge street lights
System Design	Floating waterwheel power generator system designed to harness the power of flowing water in rivers and canals
Floats	Aerodynamically designed floats made from fiber resin material and anchored in the flowing water body using steel wires
Waterwheel and Generator	FRP blades on a shaft rotate due to the flow of water, coupled with a specially designed generator that is waterproof, brushless, slip-ringless, and resin sealed. The generator produces AC power
Power Output	Power output ranged from 60W to 250W, depending on the flow rate of water
Independence from External Grid	The system functions without needing electricity from the external grid, making it self-sustaining and independent
Relationship between Flow Rate	The linear relationship observed between the flow rate of water and the power generation
Daily Power Output Estimate	The estimated average power output of 2.4 kW/hr based on an assumed average water flow of 4.4 cusecs, indicating the potential of the system for providing clean and renewable energy from water streams

FIGURE 5. Floating power generator on site [54].

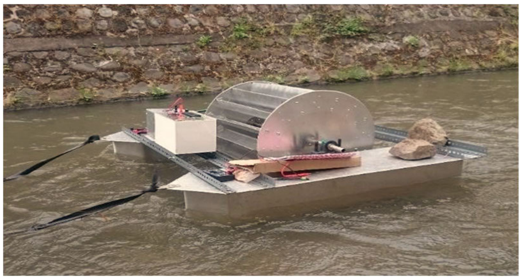


FIGURE 6. Transportable movable pico-hydro [61].

TABLE 8. Summary of design aspects and key findings.

Design Aspect	Key Findings
Design Objective	Provide a portable, cost-effective, and ecologically friendly solution for electricity generation in areas with rivers and springs
Study Area	Malang City, Indonesia, selected for its geographical characteristics and abundant rivers and springs with rapid flow
System Design	PFPH system featuring a floating waterwheel power generator
Waterwheel Design	Waterwheel with 16 closed blades, resembling a Pelton turbine design
Material	Aluminum used for stability and aerodynamic properties
Power Generation	A permanent magnet DC generator is integrated into the system to convert rotational energy into electrical power
Electricity Regulation	Controller and DC-DC converter used to regulate the generated electricity
Power Output	Power output ranged from 3W to 205W, depending on the water flow speed
Ecological Impact	Minimized ecological impact by harnessing river flow energy without creating water reservoirs or damming rivers
Feasibility and Cost-Effectiveness	Demonstrated potential for electricity generation in remote areas with rivers and springs, where conventional hydropower projects may not be feasible or cost-effective

it a renewable energy-based solution. The methodology employed in this case study involved the fabrication and working of the system. The base of the system consists of floats that are designed aerodynamically and made from fiber resin material. These floats are anchored in the flowing water body using steel wires. The chassis of the system is fabricated from hot dip galvanized MS material to protect it from corrosion. The system incorporates FRP (Fiber Reinforced Plastic) blades on a shaft, which rotate due to the flow of water. A specially designed generator, which is waterproof, brushless, slip-ringless, and resin sealed, is coupled with a gear having a ratio of 1:10. The generator is driven by the rotating shaft and produces AC power [54].

The generated power can be directly used or stored in a battery for later use. The system does not need electricity from the external grid to function, making it self-sustaining and independent. It is a portable unit that can be easily shifted to different locations as needed as depicted in Figure 5. The use of non-corrosive and unbreakable materials such as mild steel and fiberglass ensures the durability and longevity of the system. The case study highlights the effectiveness and feasibility of the floating waterwheel power generator system. The system proved to be a unique and innovative solution for harnessing the power of flowing water in rivers and canals.

The performance of the floating generator system was evaluated by conducting on-site testing in a canal. The output power of the system was measured for different flow rates of water between the floats, ranging from 3.5 to 6 cusec. The result is presented in Table 7 showing a power output of range 60 to 250 watt. Based on this result, estimation was made for the daily power output of the system, assuming an average water flow of 4.4 cusecs. The estimated average power output was 2.4 kW/hr, which indicates the potential of the floating generator system for providing clean and renewable energy from water streams. It offers several advantages, including village electrification, agricultural water pumping, and bridge street lighting, without the need for permanent installations or external power sources.

C. CASE STUDY 3

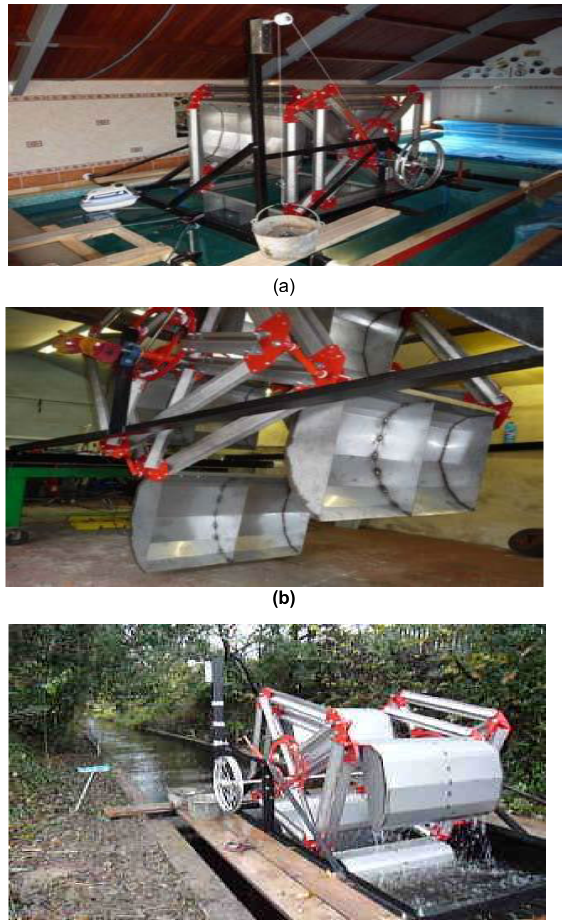
The presented case study focuses on the design and implementation of a portable floating pico-hydro (PFPH) system, specifically a floating waterwheel power generator. The methodology employed in this study aimed to create a renewable and ecologically friendly solution for generating electricity in areas with rivers and springs. The system was designed to be portable, cost-effective, and easy to maintain [61]. To begin with, the researchers selected Malang City in Indonesia as the study area due to its geographical characteristics, including an altitude between 440-667 meters above sea level and an abundance of rivers and springs with rapid flow. The goal was to harness the river flow energy without creating water reservoirs or damming rivers, thus minimizing ecological impact. The floating waterwheel design was chosen as it could efficiently utilize the kinetic energy stored in the flowing water [62].

The PFPH system was constructed using materials such as aluminum, which provided stability and aerodynamic properties. The overall mechanical design of the system included a waterwheel with 16 closed blades, resembling a Pelton turbine design. The undershot water wheel was positioned in the river, with the water level always below the wheel axis as illustrated in Figure 6. This allowed the water flow to create a pushing action against the submerged paddles, resulting in the rotation of the wheel in one direction.

A permanent magnet DC generator was integrated into the system to convert the rotational energy of the waterwheel into electrical power. The generator's specifications, including length, diameter, nominal speed, voltage, and current, were carefully considered to ensure efficient power generation. The generated electricity was regulated using a controller and a DC-DC converter, and a battery was employed as a load for storing the electrical energy. The performance of the floating waterwheel power generator system was tested by varying the water speed from 1 m/s to 4 m/s and got the power output between 3 to 205 watts is shown in Table 8. The power output ranged from 3W to 205W, demonstrating the system's capability to generate electricity efficiently. The design and implementation of the PFPH system aimed to provide a renewable and environmentally friendly solution for electricity generation. The system demonstrated promising performance, generating a significant amount of power within the tested water speed range. The use of a floating waterwheel allowed for easy installation and maintenance without the need for damming or reservoir construction. Overall, the study highlighted the potential of such systems in remote areas with rivers and springs, where conventional hydropower projects may not be feasible or cost-effective.

D. CASE STUDY 4

In [63] authors focuses on the design, development, testing, and evaluation of a novel floating hydro generator. The objective is to enhance power transmission and efficiency by introducing a unique paddle-shaft linkage mechanism. The prototype of the undershot water-wheel floating generator (FG) was tested in two field trials: a swimming pool with low-flow conditions and a millstream to simulate normal flow conditions. The results demonstrated that the FG achieved an efficiency of 55-69%, which is comparable to the best performances reported in the literature [64]. The floating design of the water wheel allows for unrestricted movement of aquatic life beneath it, eliminating the need for disruptive construction of barrages or other permanent structures [65]. This study provides valuable insights for further optimization of the FG design to achieve even higher efficiencies. Waterwheels have been historically used to harness the kinetic energy of flowing water for mechanical work and power generation. Traditional designs utilized radially extending paddles, resulting in limited efficiency and scope for improvement [66]. However, advancements in hydraulic engineering, material science, and computer-aided design have allowed for significant enhancements in waterwheel performance. In this research, a prototype of the undershot



(a) (b) (c)

FIGURE 7. The figures illustrative design and operation of the floating hydro-generator: (a) FG hydro generator with vertical paddles, (b) The pulley mechanism with a bucket, (c) Millstream setup with constant water flow and longer string to lift weights [64].

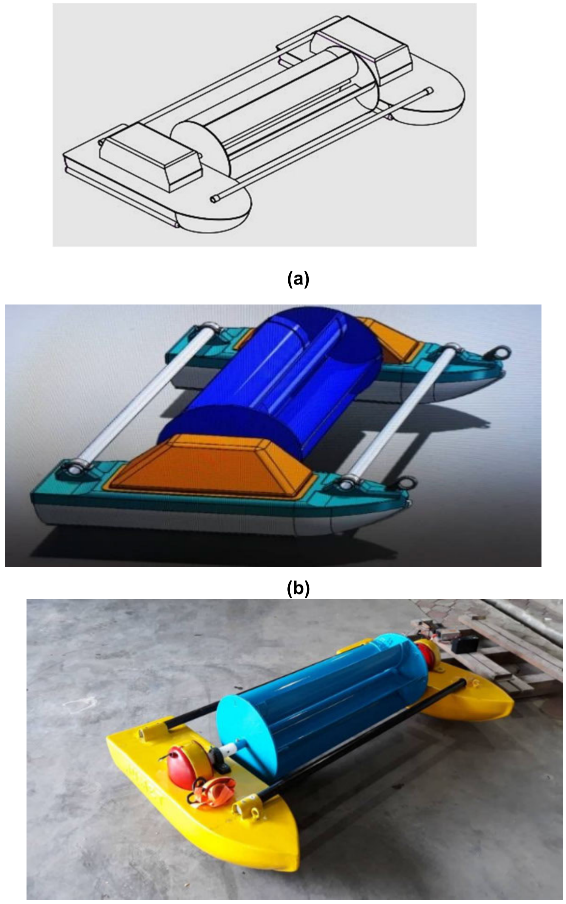
TABLE 9. Summary of key findings.

Design Aspect	Key Findings
Design Objective	To enhance power transmission and efficiency of a floating hydro-generator
Prototype Design	Undershot water-wheel FG with a unique paddle-shaft linkage mechanism
Field Trials	Conducted in a swimming pool and a millstream
Efficiency Achieved	FG achieved an efficiency of 55-69%, comparable to the best performances reported in the literature
Environmental Impact	Floating design allows unrestricted movement of aquatic life and eliminates the need for disruptive construction
Further Optimization	Valuable insights were provided for optimizing the FG design to achieve even higher efficiencies
Millstream Trials	Accurate measurement of power input using paddle area and water velocity
Real-world Validation	Performance of the FG validated in real world conditions

water-wheel FG was developed, incorporating an innovative linkage mechanism to maximize power transmission and efficiency is illustrated in Figure 7. The FG floating design ensures minimal disruption to the environment and allows for installation in various water streams without the need for additional structures.

The design of the FG involved circular-arc-shaped paddles made of aluminum, arranged in a configuration that optimizes power extraction from the water flow. The prototype was tested in two different field trials: a swimming pool and a millstream. In the swimming pool experiments, the power available to the paddles was estimated using computational fluid dynamics simulations, considering the flow velocity and volumetric flow rate of water [67]. The output power from the FG was measured using a pulley and weight mechanism at different distances from the water jets. The millstream trials involved subjecting the FG to a steady water velocity, and the power input to the generator was determined experimentally by measuring the area swept by the paddles and the stream velocity. During the millstream trials, the FG was exposed to a constant water velocity of 0.63 m/s. To determine the power input to the generator, the researchers measured the area of the paddle normal to the water flow and the stream velocity. The formula $P_i = \frac{\rho A u^3}{2}$ was utilized, where Pi represents the power input, A is the paddle area, u is the water velocity, and ρ is the density of water. By collecting these data, the researchers obtained accurate measurements of the power input to the FG in the millstream environment. Figure 7 provides an illustrative representation of the design and operation of the floating hydro-generator, showcasing (a) the FG hydro generator with vertical paddles, (b) the pulley mechanism with a bucket, and (c) the millstream setup with a constant water flow and a longer string used to lift weights.

The research demonstrates the successful design, development, testing, and evaluation of an innovative floating hydro-generator [64]. Table 9 summarizes the important



(a)

(b)

(c)

FIGURE 8. Design and development of a floating waterwheel turbine: (a) Concepts, (b) Model Design, (c) Prototype Development [71].

findings of this research from design perspectives. The prototype, equipped with a unique paddle-shaft linkage mechanism, achieved an efficiency of 55-69% during field trials, closely approaching the best performances reported in the literature for undershot water wheels. The floating design of the FG allows for unrestricted movement of aquatic life and eliminates the need for disruptive construction. The findings from this study provide valuable insights for optimizing the current design and aiming for even higher efficiencies. The case study of the millstream trials showcases the accurate measurement of power input using the area of the paddles and water velocity, further validating the performance of the FG in real-world conditions.

E. CASE STUDY 5

The study focuses on the design process and analysis of a Pico hydroelectric floating waterwheel turbine. The researchers aim to harness the hydrokinetic energy from open streaming water to generate electricity for local power needs [68]. The research outlines key design parameters, tools, and methods for the engineering characteristic rank arranged according to the customer's requirements. Quality Function Development (QFD) is employed to ensure the design meets the desired

TABLE 10. Summary of key findings.

Design Aspect	Key Findings
Design Objective	To optimize the design of a Pico hydroelectric floating waterwheel turbine for continuous electricity generation
Design Analysis Techniques	Design for Assembly, Morphology analysis
Types of Water Wheels Analyzed	Undershot, Savonius
Efficiency of Undershot Waterwheels	Curved blade tip exhibited higher efficiency, reaching up to 77%
Impact of Water Kinetic Energy	The use of a floating waterwheel blade demonstrated better energy exchange
Optimal Number of Blades for Savonius Waterwheels	Eight-blade waterwheel showed the highest efficiency
Comparative Analysis of Performance	A higher number of blades led to better performance and increased efficiency
Empirical Data	At a flow rate of 0.01587 m3/s and a shaft load of 1000 grams, the waterwheel with 8 blades achieved an efficiency of 17.056%

specifications [69]. Various design analysis techniques such as Design for Assembly and Morphology analysis are utilized for concept generation. The study concludes with the proposal and evaluation of a new design for a floating waterwheel prototype that successfully meets the requirements for electricity generation [70]. The concern for renewable energy resources to meet the growing electricity demand has led to the exploration of various technologies. In this research, the focus is on utilizing water resources through the implementation of a waterwheel turbine. Waterwheel technology, specifically the breastshot wheel, is considered suitable for small-scale hydropower plants. The study aims to optimize the design of the waterwheel turbine to provide continuous electricity based on a water stream source fund. Different types of water wheels, including overshot, undershot, and breastshot waterwheels, are explored in terms of their efficiency and performance. Figure 8 presents a comprehensive overview of the design and development process of a floating waterwheel turbine, including concept design, model design, and prototype development.

The researchers conducted experiments and theoretical modeling to evaluate the performance of water wheels. The study found that for undershot waterwheels, those with a curved blade tip exhibited higher efficiency, reaching up to 77% [72]. The analysis also examined the impact of water kinetic energy on the vitality transformation process in the underwater wheel. Additionally, the study explored the use of a floating waterwheel blade, which demonstrated better energy exchange due to its movement and interaction with the water flow [73]. Based on the analysis, an eight-blade water wheel was found to be the most efficient. This comparative analysis of the performance of Savonius waterwheels with different numbers of blades (4, 6, and 8) at specific flow rates and shaft loads [74]. The results indicate that a higher number of blades leads to better performance and increased efficiency. For instance, at a flow rate of 0.01587 m^3/s and a shaft load of 1000 grams, the waterwheel with 8 blades achieved an efficiency of 17.056%, compared to 9.945% and 13.929% for 4 and 6 blades, respectively. This empirical data suggests that the number of blades significantly affects the performance of Savonius waterwheels.

The research paper focuses on the design process and study of a Pico hydroelectric floating waterwheel turbine. The research's main conclusions from several design perspectives are displayed in Table 10. The study highlights the efficiency and performance of different types of water wheels, including undershoots and Savonius water wheels.

F. CASE STUDY 6

The case study focuses on the methodology and conclusion results of a floating waterwheel power generator system. This innovative project aims to develop a sustainable energy solution for remote areas by utilizing the power of water flow. The process includes designing and building a floating hydropower plant that includes a Pico hydro turbine, generator, and control system. The project starts by designing a floating structure that can support the waterwheel and other components. The waterwheel is carefully designed, considering parameters such as blade tilt angles and water flow velocity to optimize energy conversion. The integration of an undershot waterwheel allows for efficient power generation. A DC generator is strategically included in the system to convert the mechanical energy of the waterwheel into electrical energy [53]. To ensure that the power generation system is monitored and controlled in real time, IoT technology is incorporated. This enables the visualization of essential electrical parameters through mobile apps, providing remote oversight. The use of IoT technology enhances the efficiency and reliability of the power generation system. The methodology is validated through a comprehensive testing process. A MATLAB/Simulink model simulation is conducted to evaluate the system's performance. Prototype testing is also carried out in a canal to gather practical data and analyze the system's efficiency under real-world conditions as shown in Figure 9. The results and analysis obtained from these tests provide valuable insights into the system's performance and highlight its potential for future applications. Based on the conclusion results, the floating waterwheel power generator system proves to be a promising and sustainable solution for addressing energy scarcity in remote areas. The system offers a reliable and eco-friendly power source, particularly for off-grid communities that lack access to conventional energy infrastructure. The flexibility and adaptability of the floating structure make it suitable for deployment in rivers and water bodies, further expanding its potential impact. By harnessing the power of water flow, the system can significantly alleviate energy deficits in underserved areas and contribute to the global demand for renewable energy solutions.

During the testing phase, the researchers measured the power generated by the system under different operating conditions. Table 11 summarizes the conclusions of this study

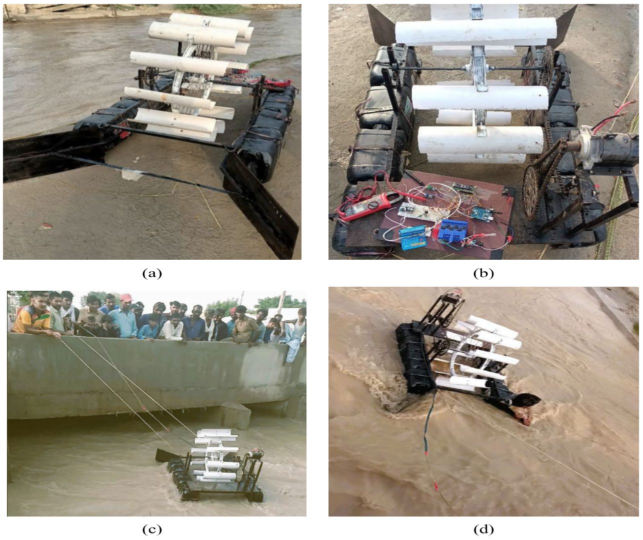


FIGURE 9. Photographs of the developed prototype of an autonomous and floating hydropower plant [53].

TABLE 11. Summary of design aspects and key findings.

Design Aspect	Key Findings
Design Objective	Develop a sustainable energy solution for remote areas by utilizing the power of water flow
System Components	The floating structure, Pico hydro turbine, generator, control system, IoT technology
Waterwheel Design	Parameters considered: blade tilt angles, water flow velocity; Undershot waterwheel for efficient power generation
Power Output	Maximum power generated: 204 watts
IoT Technology Integration	Real-time monitoring and control capabilities enhance system efficiency and reliability
Suitability for Remote Areas	Independent power source for off-grid communities; Adaptability to different water flow conditions; Enhances quality of life, economic activities, and access to education and healthcare facilities

from several design perspectives. These measurements were used to determine the maximum power output of the system. The maximum power generated by the floating waterwheel power generator system was found to be 204 watts. The integration of IoT technology enhances the system's efficiency by providing real-time monitoring and control capabilities.

This ensures optimal performance and enables remote oversight, making the system a reliable source of power generation. The case study of the floating waterwheel power generator system demonstrates the successful development of an automatic and sustainable hydropower solution. The methodology employed in the design and construction of the system, along with the integration of IoT technology, showcases the potential for future innovations in renewable energy generation. By addressing key challenges such as high costs, complex installation, and lack of monitoring, this system offers a low-cost, easy-to-install, and remotely monitored solution for powering remote and rural areas. The floating

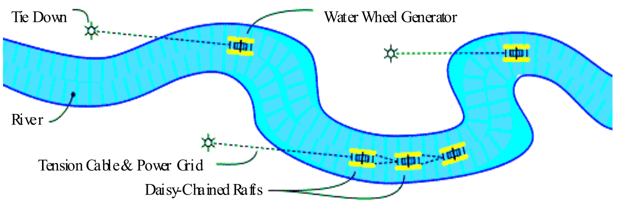


FIGURE 10. Several floating water-wheel generators can be linked in series to multiply the amount of electricity produced [55].

waterwheel power generator system exhibits several advantageous features, including high efficiency, low maintenance requirements, and suitability for remote areas. These qualities make it a viable and practical solution for addressing energy needs in such locations. Efficiency is a key aspect of the system, ensuring optimal energy conversion from the water flow into electrical power. The design of the waterwheel, with considerations for blade tilt angles and the number of blades, aims to maximize energy extraction from the flowing water. By optimizing the design parameters, the system can achieve high conversion efficiency, leading to an improved power generation capacity. This efficiency is crucial in remote areas where energy resources may be limited, as it allows for the utilization of available water flow to generate a significant amount of electricity. Figure 10 illustrates the potential for increased electrical power generation by connecting multiple floating water-wheel generators in series, demonstrating the scalability and versatility of this technology.

Another advantage of the floating waterwheel power generator system is its low maintenance requirements. The simplicity of the design, with fewer moving parts compared to other hydropower systems, reduces the need for regular maintenance and upkeep. The absence of complex components and the use of durable materials contribute to the system's reliability and longevity [75]. This low maintenance requirement is especially beneficial in remote areas where access to skilled technicians and spare parts may be limited. The suitability of the system for remote areas is a key aspect of its design and implementation. Off-grid communities often face challenges in accessing reliable and affordable electricity. The floating waterwheel power generator system offers a decentralized and independent power source that can be deployed in rivers and water bodies near these communities. Its adaptability to different water flow conditions and scalability make it suitable for a variety of remote locations. By bringing electricity to these areas, the system can improve the quality of life, enable economic activities, and enhance educational and healthcare facilities. The system's sustainability and eco-friendliness align with the growing global demand for renewable energy solutions [76]. It utilizes the natural power of water flow, a clean and abundant resource, to generate electricity. By reducing dependence on fossil fuels and minimizing carbon emissions, the system contributes to mitigating environmental impacts and combating climate change. The floating waterwheel power generator system offers high efficiency, low maintenance requirements, and suitability for remote areas. Its efficient energy conversion, coupled with its simplicity and durability, ensures optimal power generation with minimal upkeep. The system's adaptability and independence from traditional energy infrastructure make it a practical solution for addressing energy needs in remote communities. By harnessing the power of water flow, the system provides a sustainable and eco-friendly source of electricity, improving the lives of people in off-grid areas and contributing to a greener future.

G. MODELLING OF THE SYSTEM DYNAMICS OF WATERWHEEL SYSTEMS

In this section discussing the need for more comprehensive exploration and modeling of waterwheel systems within case studies.

1) RELATIONSHIP BETWEEN FLOW RATE AND EFFICIENCY

Discuss how variations in the flow rate affect the efficiency of the waterwheel system. This could involve examining how changes in water flow impact the rotational speed of the wheel and subsequently influence power generation efficiency [77].

2) TYPE OF POWER GENERATION AND STABILITY

Explore the type of power generation employed by the waterwheel system (e.g., mechanical, electrical) and its stability under different operating conditions. This could involve analyzing how the system responds to fluctuations in water flow or external disturbances [78].

3) RELIABILITY FACTOR

Assess the reliability of the waterwheel system by examining factors such as maintenance requirements, lifespan of components, and overall system robustness [79].

4) ECOLOGICAL EFFICIENCY

Consider the ecological impact of the waterwheel system, including its effects on the surrounding environment and wildlife. This could involve evaluating aspects such as habitat disruption, water quality, and potential mitigative measures to minimize adverse effects [80].

H. COMPARISON BETWEEN FLOATING WATER WHEEL AND STANDARD HYDROPOWER PLANT

The design, size, and efficiency of a normal hydropower plant and a floating waterwheel vary, but both use the energy of flowing water to produce electricity. A quick comparison of the two is provided below [81].

1) FLOATING WATERWHEEL

- Usually comprised of a buoyant platform with buckets or blades coupled to a horizontal wheel.
- Water rushes over the wheel, transferring its kinetic energy into mechanical energy as the wheel revolves.
- It can be installed in rivers, streams, or other bodies of water and is frequently utilized in smaller-scale applications [82].

2) STANDARD HYDRO POWER PLANT

- It involves more extensive and sophisticated infrastructure, such as a penstock to direct water into a turbine and a dam to produce a reservoir.
- Turbines can be either horizontal or vertical, depending on the design.
- The turbine, which is attached to a generator, is turned by the force of flowing water to generate power [83].

Floating converter dimensions are determined by the particular technology and capacity. These might be more substantial structures included into the floating renewable energy system, or they could be smaller electronic parts. Floating converters are notable for their efficiency, power rating, voltage management, and compatibility with storage systems and the electrical grid. Potential drawbacks could include corrosion, vulnerability to environmental factors including exposure to water, and difficulties performing maintenance and repairs in aquatic settings [84].

IV. THEORETICAL DESIGN FOR FLOATING WATERWHEEL POWER GENERATION

Designing a floating waterwheel for power generation involves several key considerations, including the selection of materials, the design of the wheel, and the integration of power generation components. Here's a theoretical design based on previous approaches:

A. SELECTION OF MATERIALS

Since the waterwheel will be floating, it needs to be constructed from lightweight yet durable materials that can withstand exposure to water. Fiberglass, aluminum, or reinforced plastic could be suitable choices for the wheel's structure [85].

B. WHEEL DESIGN

The waterwheel should be designed to efficiently capture the kinetic energy of flowing water. A traditional paddle wheel design with large, flat paddles is effective for this purpose [86]. The wheel should be large enough to capture a significant amount of water flow, but not so large that it becomes unwieldy or difficult to manage [87].

C. FLOATATION SYSTEM

The waterwheel will need to be buoyant enough to float on the surface of the water. This could be achieved by incorporating buoyant materials such as foam or hollow chambers into the wheel's structure [88]. Additionally, the wheel could be supported by pontoons or floats attached to the sides [89].

D. ANCHORING MECHANISM

To keep the waterwheel in place and prevent it from drifting away, an anchoring mechanism is necessary. This could involve attaching the wheel to a stationary structure on the shore or using anchors or mooring lines to secure it in place [90].

TABLE 12. Summarizing the environmental and economic impacts of floating waterwheel power generators.

Aspect	Description
Environmental Benefits	Utilizes the natural flow of rivers and canals, minimizing environmental disruption.
	Low environmental impact, as it does not require dams or significant water diversion.
	No direct greenhouse gas emissions, contributing to reduced carbon footprint.
	Minimal impact on aquatic ecosystems, allowing fish and other aquatic life to pass through safely.
Economic Feasibility	Economically viable in regions with suitable water flow conditions, especially in developing areas.
	Low operating costs due to absence of fuel expenses and minimal maintenance.
	Can contribute to rural electrification, potentially boosting local economies and improving living conditions.
Cost-Effectiveness	Relatively low initial setup costs compared to traditional hydropower or fossil fuel-based power generation.
	Scalability allows for custom designs to meet specific energy needs and budgets.
	Long operational life with minimal maintenance costs enhances the cost-effectiveness of the technology.

E. POWER GENERATION COMPONENTS

The waterwheel will be connected to a generator to convert mechanical energy into electrical energy. The generator could be housed either on the wheel itself or on a separate platform nearby [91]. Depending on the scale of the project, the generator could be a small-scale hydroelectric turbine, a dynamo, or an alternator [92].

F. TRANSMISSION SYSTEM

A transmission system is needed to transfer the rotational motion of the waterwheel to the generator. This could involve a system of gears, belts, or chains, depending on the specific design of the wheel and the generator [93].

G. MONITORING AND CONTROL SYSTEMS

To optimize the performance of the waterwheel and ensure safe operation, monitoring and control systems should be integrated [81]. This could include sensors to measure water flow and wheel rotation speed, as well as controls to adjust the wheel's position or speed as needed [94].

H. ENVIRONMENTAL CONSIDERATIONS

It's important to consider the potential environmental impact of the waterwheel, particularly in terms of wildlife habitat and water quality [95]. Care should be taken to minimize disruption to the natural ecosystem and to comply with any regulatory requirements [96].

V. NATIONAL GRID INTEGRATION TOPOLOGY

The literature now in publication delves deeply into a number of aspects of hydropower integration and associated technologies [53]. Examine the elements and environmental implications of traditional hydropower in [92], with a focus on pumped storage and grid integration. The modeling, simulation, and construction of an undershot floating waterwheel are presented in [60], illustrating how the velocity of the water flow affects power output. In [97], the integration of renewable energy sources, such as micro hydropower, has been studied. Hybrid photovoltaic systems and micro-hydropower systems are suggested for a continuous power supply. Grid integration and environmental consequences are two major issues faced by traditional hydropower projects [98]. Micro-hydroelectric power plants are a sustainable alternative, although the dependability of hybrid photovoltaic systems can be impacted by variations in solar irradiance. It is emphasized that tiny electric power users should choose their generator carefully [99]. Grid connectivity and load balancing solutions are necessary for the management of micro-hydropower systems for rural electrification [100]. Although wastewater discharge has the potential to generate electricity, there are design challenges when switching from large-scale hydropower to low-head systems [101]. Although floating power generators are attractive, their scalability and applicability in the actual world need to be assessed [102]. In [78]a fixed water source low head micro hydropower system's methodologies are analyzed, evaluated, and systematically represented, along with the design of a water wheel for the system. This is a backup system for the national grid that is meant to keep a home powered in the event that the main grid fails. During the off-peak hours, water is pushed up to the upper reservoir and released via the turbine when needed to produce energy. This system uses a fixed volume of water that circulates through the turbine and is stored in a lower reservoir.

VI. ENVIRONMENTAL AND ECONOMIC IMPACTS

Exploring the environmental and economic facets of floating waterwheel power generators sheds light on their positive ecological footprint and cost-effectiveness, highlighting their potential as a sustainable energy solution [103]. These generators harness river water resources without the need for dams or significant water diversion, thereby minimizing environmental disruption. Additionally, their minimal impact on aquatic ecosystems ensures the safe passage of fish and other aquatic life [104]. The efficiency of a new waterwheel design, capable of handling over four times the water volume per meter width compared to traditional designs, demonstrates significant potential for generating power, with an estimated annual investment return of 7.5% over a century on a 2.5 m high weir in the United Kingdom (UK) with 5 m3/s mean flow. Meanwhile, innovative prototypes have achieved impressive results, such as a maximum power output of 1.2 kW and an overall efficiency of 32.5% [105]. Economically viable, particularly in developing regions, these generators offer low operating costs and minimal maintenance, thus aiding rural electrification and potentially boosting local economies. With their relatively low initial setup costs and scalability to meet diverse energy needs, floating waterwheel power generators emerge as a cost-effective and environmentally friendly alternative to traditional hydropower plants, thereby enhancing the sustainability of energy production [106]. Here Table 12 shows the environmental and economic impacts of floating waterwheel power generators.

1) GREEN ENERGY FRACTION

Calculate the proportion of energy generated by the waterwheel system that can be considered "green" or renewable [107]. This involves assessing the system's environmental impact compared to conventional energy sources and quantifying its contribution to reducing greenhouse gas emissions [108].

2) CARBON FOOTPRINT

Estimate the carbon footprint associated with the entire lifecycle of the waterwheel system, including manufacturing, installation, operation, and decommissioning [109]. This involves quantifying emissions of greenhouse gases such as carbon dioxide (CO_2) and methane (CH4) and assessing their environmental impact [110].

3) ECOLOGICAL IMPACT

Evaluate the ecological impact of the waterwheel system on the surrounding environment, including factors such as habitat disruption, water quality, and impact on wildlife [80]. This could involve conducting environmental assessments and incorporating mitigation measures to minimize adverse effects [111].

4) ECONOMIC PARAMETERS

a: NET PRESENT VALUE (NPV)

Calculate the NPV of the waterwheel system by discounting future cash flows associated with its installation, operation, and maintenance to determine its profitability over its lifecycle [112].

b: LEVELIZED COST OF ENERGY (LCoE)

Estimate the LCoE of the waterwheel system, which represents the average cost of generating one unit of electricity over its operational lifetime. This involves considering initial investment, operating costs, and energy output [113].

c: LPSP (LOSS OF POWER SUPPLY PROBABILITY)

Assess the LPSP of the waterwheel system, which indicates the likelihood of power supply interruptions under different scenarios. This involves analyzing system reliability, maintenance schedules, and potential failure modes [114].

d: ECOLOGICAL IMPACT

Numerous studies, however widely dispersed, documented various ecological effects brought about by modest RoR hydropower plants connected to three common hydroelectric schemes. Changes in flow regimes, such as flow depletion in the de-watered river reach, particularly in the diversion weir, and huge instantaneous flow discharges through turbines in the pondage hydropower scheme, are the main ecological effects caused by small RoR hydropower facilities [13].

TABLE 13. Key aspects of experimental research and efficiency optimization.

Aspect	Description
Performance Testing	Testing the system under various conditions, measuring power output, efficiency, and performance in controlled environments.
Optimization of Design Parameters	Fine-tuning design parameters, including blade geometry, material, and dimensions, using computational modeling and simulations.
Material Selection	Choosing lightweight, durable, and cost-effective materials to withstand the water environment and reduce maintenance.
Blade Design	Investigating blade profiles, angles, and shapes to maximize energy capture and minimize losses, considering the angle of attack.
Load Matching	Developing control systems to match the generator's load to variable water flow conditions and maintain optimal operation.
Hydraulic Efficiency	Reducing hydraulic losses, improving water flow distribution, and minimizing turbulence to enhance overall hydraulic efficiency.
IoT and Monitoring	Integrating IoT technology for real-time monitoring and control, enabling data collection for optimization and remote management.
Environmental Impact Assessment	Assessing the system's impact on aquatic ecosystems, ensuring ecological sustainability without harm to aquatic life.
Scalability and Adaptability	Investigating modular designs that facilitate transportation and assembly in diverse water bodies and flow conditions.
Simulation and Modeling	Using advanced tools like CFD and FEA to predict system behavior under different conditions and guide design modifications.

By including these ecological and economic parameters in their study, authors can provide a comprehensive evaluation of the waterwheel system's effectiveness, sustainability, and economic viability. This multidimensional analysis facilitates informed decision-making and promotes the adoption of environmentally friendly and economically feasible renewable energy solutions.

A. IMPLICATIONS FOR SUSTAINABLE ENERGY LANDSCAPES

The concept of energy landscapes is not new. The fact that humans have domesticated animals is the first step toward the creation of a multitude of energy landscapes (EL). Making a distinction between the idea of an energy landscape and the actual energy landscape is advantageous. Many have examined how the physical energy landscape has changed over time. One of the leading experts on EL discourse, Pasqualetti, has delineated four stages.

Stage 1:

EL of the organic economy with energy derived from wind, water, and wood.

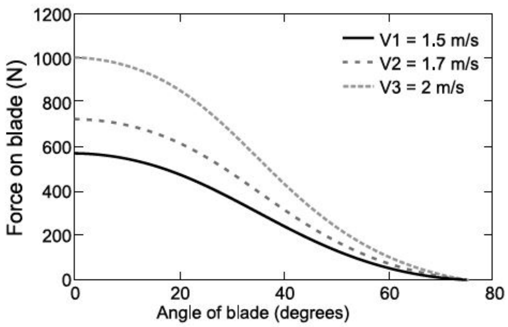


FIGURE 11. Force applied to the blade while the wheel's blade rotates at various flow rates [60].

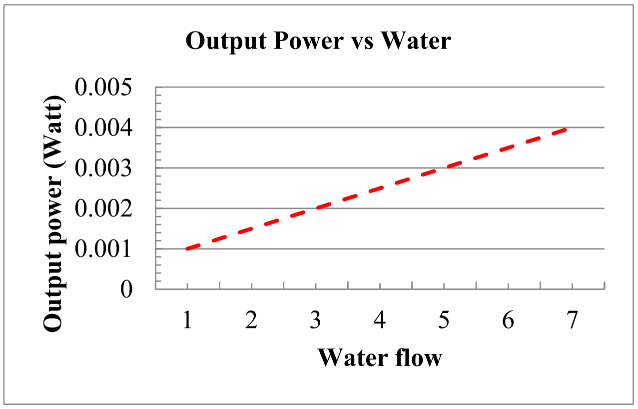


FIGURE 12. Output power vs water flow.

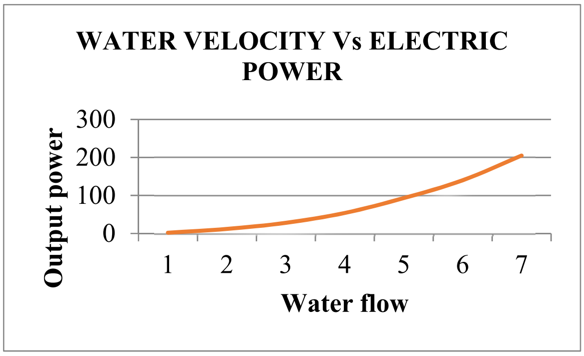


FIGURE 13. Power curve.

Stage 2:

The mining economy's EL makes use of unconventional fossil fuels, coal, oil, and natural gas.

Stage 3:

EL of the electricity economy is defined by a substantial nuclear fuel supply and electrical infrastructure.

Stage 4:

Energy-based sustainable economy uses hydropower, geothermal, wind, and solar energy, as well as biomass.

It becomes evident that throughout history, energy and landscape have been inextricably linked [115].

VII. EXPERIMENTAL RESEARCH AND EFFICIENCY OPTIMIZATION

Experimental research and efficiency optimization are paramount in advancing the development and efficacy of floating waterwheel power generators, aiming to improve their performance, reliability, and cost-effectiveness. Table 13 highlights the ongoing processes of efficiency optimization and experimental research, crucial for addressing challenges and making these generators more effective, reliable, and widely applicable. These endeavors contribute significantly to maximizing the efficiency of renewable energy extraction from flowing water sources while minimizing environmental impact. In this context, the studies analyzed in this research paper underscore the importance of quantitative analysis in enhancing the performance of hydrokinetic power converters. For instance, experiments conducted on a floating hydro-generator prototype showcased significant efficiency improvements through design modifications. Another study introduced a novel waterwheel design for very-low-head hydropower schemes, achieving an efficiency rate of 55-69% for modern waterwheels [64]. Furthermore, modeling and simulation techniques were utilized to assess the performance parameters of an undershot waterwheel, indicating potential optimizations in design to enhance overall efficiency. These findings collectively emphasize the critical role of experimental research and efficiency optimization in advancing hydrokinetic power converters, thus promoting improved environmental sustainability and economic viability.

In case study1the drag force exerted on wheel blades exhibits comparable behavior due to its reliance on relative velocity, as illustrated in Figure 11.

$$F(Q) = 750 xwxdxV^{2} (Cos\theta - 0.33)^{2} \quad (1)$$

The computation is done using equation 1, and the simulation uses the values of blade height (d = 0.5 m) and blade width (w = 1.5 m). Drag force reduces as the blade's rotational angle increases, and this is explained by the decline in relative velocity. The flow velocity can also be affected.But because there is no relative velocity at that point, the force is zero. At this point, water no longer exerts any force on the blade; instead, the blade must now exert force on the water in order to pass through it [116].

Observations were made during our floating generator system's on-site testing, as documented in case study 2 by [54]. Figure 12 displays the graph. An approximation was created for a generation of a day based on the data. The following technical specifications and an average water flow rate of 4.4 cusec between the floats are used in the computation. According to the aforementioned parameters, 2.4 KW/hr of power were produced on average per day at a water flow rate of 4.4 cusec.

Portable Floating Pico-Hydro (PFPH) has been evaluated in [61] case study 3 by monitoring changes in river flow velocity in response to variations in power output. Figure 13 depicts the outcomes of the inhibition.The data indicates that a change in flow velocity causes a logarithmic increase in power production. It generates 205 watts of power at a flow rate of 4 m/s.

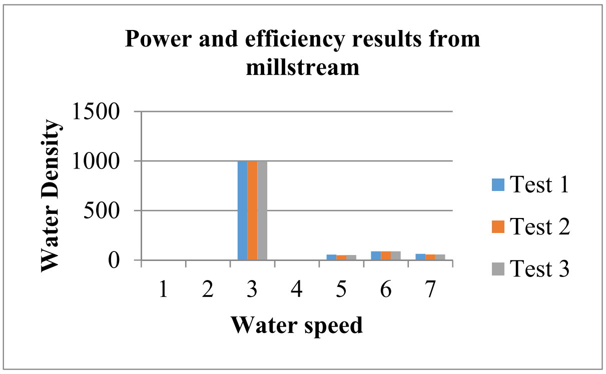


FIGURE 14. Efficiency and power are produced by millstream.

The power and efficiency seen in the millstream trials are compiled in Figure 14 in [64] from case 4. In comparison to the swimming pool studies, the maximum power achieved in the millstream experiments is 55 W with an efficiency of 62.1%, which is 7.6% less. The efficiency of the F-Gen from both trials was validated by comparing them with the undershot water wheel results published by [117]. The efficiencies were found to be in close accord with the literature, indicating the validity of the experimental and mathematical techniques. The device was operating effectively, as demonstrated by the experiments conducted in the millstream, with efficiencies ranging from 55.7 to 62.1%. This performance was equivalent to the highest documented performance for undershot water wheels (65%) in the literature [118].

VIII. PRACTICAL APPLICABILITY AND ADVANTAGES PORTABLE WATERWHEEL DESIGN FOR LOW HEAD HYDROPOWER

The practical applicability and advantages of the new, more efficient waterwheel design for very-low-head hydropower schemes, divided into four sections:

A. VERSATILE DEPLOYMENT

The new waterwheel design is suitable for very-low-head hydropower schemes, which are characterized by low vertical drop heights. This makes it applicable to a wide range of locations, including rivers, canals, and other watercourses [119].

B. URBAN INSTALLATIONS

The design's inflow system allows for installation in urban areas where riverbank land may be limited. This opens up opportunities for harnessing hydropower in densely populated regions and utilizing existing water infrastructure [120].

C. COST-EFFECTIVENESS

The new waterwheel design offers economic viability for very-low-head hydropower schemes. It has the potential to provide a high return on investment over an extended period [121].

D. LONGEVITY

The design's economic viability is further enhanced by its longevity. With proper maintenance, the waterwheel can operate efficiently for a prolonged period, contributing to sustained power generation and financial benefits [93].

E. LOW ENVIRONMENTAL IMPACT

Compared to conventional turbines, the waterwheel design has a lower environmental impact. It minimizes adverse effects on the aquatic ecosystem by not removing water from the watercourse [122]. This helps to maintain the natural flow regime and preserve the ecological balance [123].

F. FISH-FRIENDLY DESIGN

The waterwheel design incorporates features that promote fish-friendly operation. The use of higher water volumes and smoother flow reduces turbulence and provides a more favorable environment for fish passage, contributing to aquatic habitat conservation [83].

These practical applicability and advantages of the new waterwheel design for very-low-head hydropower schemes demonstrate its potential for sustainable and efficient power generation in various settings.

IX. CONCLUSION

This paper has provided a comprehensive exploration of floating waterwheel power generators, highlighting their significant potential as a sustainable energy solution for small-scale hydropower projects. Examining various case studies, demonstrated the viability and adaptability of these innovative systems particularly are in challenging, remote, and off-grid areas. Through an analysis of their environmental and economic impacts, it is underscored the positive ecological footprint and cost-effectiveness of floating waterwheels, emphasizing their ability to harness flowing water for electricity generation while mitigating direct fuel costs and enhancing sustainability. The discussion on experimental research and efficiency optimization has emphasized the importance of ongoing efforts to enhance the performance, reliability, and cost-effectiveness of these systems through performance testing, optimization of design parameters, material selection, blade design, load matching, hydraulic efficiency improvements, IoT integration, environmental impact assessment, scalability, adaptability, simulation, and modeling. This paper has provided valuable insights into the potential of floating waterwheel power generators to address energy needs while minimizing environmental impact, particularly in regions with suitable water flow conditions. As an ever-evolving branch of renewable energy, floating waterwheel power generators offer promise in the pursuit of clean and renewable energy, contributing to a greener and more electrified future. Moving forward, future research and development efforts, including advanced material research, grid integration strategies, environmental impact studies, and socioeconomic impact assessment, will be crucial in further advancing the development and implementation of these systems.

X. FUTURE WORK

A. ADVANCED MATERIAL RESEARCH

Investigate the use of cutting-edge materials with improved resistance to corrosion and wear for constructing floating structured pico hydropower plants. Exploring materials that are both durable and cost-effective can enhance the longevity and efficiency of these systems.

B. GRID INTEGRATION STRATEGIES

Explore innovative grid integration approaches for these systems to ensure seamless energy distribution. Investigate how floating structured pico hydropower plants can be effectively integrated into existing local and national grids to maximize their contribution to sustainable energy production.

C. COMMUNITY ADOPTION AND SOCIOECONOMIC IMPACTS

Investigate the social and economic implications of deploying floating structured pico hydro power plants in local communities. Assess their adoption rate, socioeconomic benefits, and the potential for empowering rural areas through improved access to clean and reliable energy.

D. HYDRAULIC OPTIMIZATION AND POWER CONVERSION EFFICIENCY

Investigating methods to enhance energy capture from flowing water and minimize hydraulic losses will be crucial for maximizing the overall efficiency of these systems. Advancements in turbine design and operational parameters can contribute significantly to improving power conversion efficiency, ultimately enhancing the performance and viability of floating structured pico hydro power plants.

Hydrokinetic power converters face challenges due to low efficiency and limited availability of suitable sites, but ongoing research aims to improve efficiency and identify optimal locations for their deployment.

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