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An Innovative Floating-Supported Cross-Flow Turbine for Hydropower Recovery from Low-Head Barrage Outflows

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Research Article

Keywords: Low-head hydropower, Floating hydropower, Cross-flow turbine, Adaptive floating structure, Barrage gates, Carbon emission mitigation

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Abstract

Large quantities of hydraulic energy are continuously dissipated downstream of barrage gates and irrigation control structures without being recovered for electricity generation. This study presents a floating-supported cross-flow turbine designed to recover this untapped energy without modifying existing hydraulic infrastructure. The system's principal innovation is a passive, adaptive lever mechanism that mechanically links a buoyant floating platform to a movable guiding vane: as the downstream water level rises or falls, the mechanism automatically re-angles the vane so that the water jet continues to strike the turbine at its optimum position, without sensors, electrical actuators, or external control. A physical model at 1:9 scale was constructed and tested on one orifice gate of Damietta Barrage, Egypt, through three successive design configurations that progressively improved jet alignment and mechanical stability. The final adaptive configuration, combined with a redesigned curved-blade runner, achieved the highest and most stable measured efficiency of the three (up to 26%). Full-scale projections indicate (51-91) MWh of electricity per gate annually, with an associated reduction of (30-53) t CO2 per year and an estimated environmental benefit of USD (428-767) $ per gate annually.

Keywords: Low-head hydropower; Floating hydropower; Cross-flow turbine; Adaptive floating structure; Barrage gates; Carbon emission mitigation

1. Introduction

Global energy demand continues to increase as a consequence of population growth, industrial development, and urban expansion. Simultaneously, concerns regarding climate change, environmental degradation, and the depletion of fossil-fuel resources have accelerated the transition toward renewable and low-carbon energy technologies. Among renewable energy sources, hydropower remains one of the most mature and reliable technologies because of its high efficiency, operational flexibility, and long service life. Despite these advantages, conventional hydropower development is generally restricted to locations with relatively high hydraulic heads and substantial storage capacity; such projects require extensive civil engineering works, high capital investment, prolonged construction periods, and significant environmental impact.

Barrages, irrigation gates, and other regulated water-control structures continuously release large volumes of water at relatively high velocity but low head; this hydraulic energy is presently dissipated without recovery. Existing hydropower technologies are frequently unsuitable for these operating conditions because they typically require permanent installations or extensive structural modifications that may interfere with the primary hydraulic function of the existing infrastructure. Recovering even a fraction of this continuously wasted energy offers an attractive opportunity to increase renewable electricity generation without constructing new dams or reservoirs.

Floating hydrokinetic turbines have been proposed as an alternative that avoids new civil works, but most reported systems target rivers, tidal currents, or open water, and few have been tested against the specific conditions of regulated barrage gates. A more fundamental limitation is that existing floating systems generally lack any mechanism for automatically maintaining alignment between the turbine

and the water jet as downstream water levels fluctuate - a near-constant condition at operating barrages, where gate settings and irrigation demand change throughout the day and across seasons. Loss of alignment directly reduces energy-conversion efficiency and can destabilize the floating structure, and most previously reported designs address this only partially, through passive buoyancy alone.

The principal engineering challenges associated with hydropower recovery from barrage outflows include inefficient utilization of the total discharge released through the gates; high installation costs associated with conventional hydropower systems; structural constraints that prevent permanent modification of existing hydraulic infrastructure; continuous fluctuation in downstream water levels and jet trajectories, which reduce turbine performance; difficulty in maintaining stable turbine alignment under variable hydraulic conditions; and transportation, installation, and maintenance limitations associated with conventional turbine systems. These challenges demonstrate the need for a low-cost floating hydropower system capable of operating efficiently under varying hydraulic conditions without affecting the structural integrity, hydraulic performance, or environmental function of existing water-control facilities.

This study addresses that gap through the development and experimental validation of a floating-supported cross-flow turbine whose central innovation is a passive adaptive lever mechanism: a mechanical linkage that couples the vertical motion of the floating platform to the angle of a guiding vane, automatically re-aiming the water jet at the turbine as water levels change, with no sensors or electrical actuators required. A physical model at 1:9 scale, representing one orifice gate of Damietta Barrage, Egypt, was constructed and tested through three successive design configurations - a basic floating turbine, an adjustable guiding vane, and finally the adaptive lever mechanism combined with a redesigned turbine runner - to isolate the contribution of each design element to overall performance. The resulting system's hydraulic performance, full-scale energy potential, and environmental benefit are evaluated in the sections that follow.

2. Literature Review

2.1 Cross-Flow Turbines for Low-Head Applications

Among available turbine technologies, the cross-flow turbine (Banki or Ossberger turbine) has attracted considerable attention for low-head hydropower applications. Previous investigations [1-3] have demonstrated that cross-flow turbines provide several advantages, including simple construction, self-cleaning capability, tolerance to suspended sediment, and stable operation under fluctuating flow conditions, while possessing a simple mechanical configuration that reduces manufacturing and maintenance cost. These characteristics make them particularly suitable for decentralized micro-hydropower systems installed within irrigation canals and river barrages.

2.2 Floating Hydropower Systems

Floating hydropower technologies have emerged as an innovative solution for overcoming many of the limitations associated with conventional fixed installations. By supporting the turbine on buoyant structures, floating systems naturally accommodate fluctuations in water level while substantially reducing civil engineering requirements. Early studies demonstrated one of the first floating micro-hydropower concepts, using floating Kaplan-type turbines [4]. Subsequently, a floating-axis turbine capable of extracting energy from river, tidal, and ocean currents while minimizing installation and maintenance cost was proposed [5]. A diffuser-augmented floating turbine intended to improve the

technical and economic performance of marine-current power generation was later introduced [6], and an innovative floating hydro-generator combining hydraulic energy recovery with river aeration was subsequently developed [7].

Other work has focused on the design and implementation of an axial hydro turbine addressing the need for renewable energy sources from small water bodies [8], and on floating hydropower plants that seamlessly integrate a Pico-hydro turbine, generator, and control system [9,12]. Collectively, these studies contribute to the understanding and development of floating hydrokinetic turbines, offering insight into design innovations, performance enhancement, and the potential for sustainable energy generation from water currents.







some types of floating turbines [12].

2.3 Floating Hydrokinetic Platforms and Research Gap

More recent work has emphasized that platform dynamics - hydrodynamic loading, motion, and mooring configuration - strongly influence the alignment between incoming flow and the turbine runner, and therefore both efficiency and structural stability [13]. Numerical investigations have shown that uncontrolled platform motion may reduce turbine performance through changes in flow direction, rotational stability, and effective flow velocity [14]. Reviews of hydrokinetic turbine technology further note that most designs are optimized for moderate-to-high flow velocities, limiting their applicability to low-head, low-velocity settings such as irrigation canals [15]. Consequently, modern floating energy systems increasingly employ semi-constrained support mechanisms that combine structural stability with sufficient flexibility to accommodate hydraulic variation.

Despite this progress, three gaps remain. First, most floating hydrokinetic research targets natural rivers, tidal currents, or offshore environments rather than regulated waterways such as barrage gates and irrigation-control structures. Second, existing floating systems generally lack an adaptive mechanism capable of maintaining turbine alignment as water levels and jet trajectories change; loss of alignment degrades both efficiency and stability. Third, few studies have experimentally validated floating turbine concepts using a physical hydraulic model representative of an actual barrage, particularly within Egypt or the wider Middle East and North Africa (MENA) region.

The present study addresses all three gaps directly. Unlike previously reported floating hydrokinetic systems, the proposed design combines a semi-constrained floating platform, a novel adaptive mechanical linkage that automatically adjusts turbine position in response to changes in water level and jet trajectory, and a locally fabricated cross-flow turbine designed for economical manufacturing

and maintenance - validated experimentally using a 1:9 physical model representing one gate of Damietta Barrage.

3. Materials and Methods

3.1 Experimental Program

The hydraulic and mechanical performance of the proposed system was evaluated using a physical model representing one orifice gate of Damietta Barrage, Egypt, constructed at a geometric scale of 1:9 at the Hydraulic Engineering Research Institute of the National Water Research Center. The experimental program focused on optimizing the floating support system, improving turbine stability, and maximizing hydraulic energy extraction under varying discharge conditions.

3.2 System Description

The proposed hydropower system (Fig. 1) consists of four integrated subsystems: (i) a floating platform, (ii) a cross-flow turbine, (iii) a steel guiding chassis, and (iv) a power-transmission mechanism. Unlike conventional hydropower installations, the entire assembly is supported by floating elements that automatically follow downstream water-level fluctuations, avoiding the extensive civil construction and structural modification that conventional installations require.



Fig. 1. The floating-supported cross-flow turbine system installed behind one gate of Damietta Barrage.

Unlike conventional hydropower installations, the proposed system is entirely supported by floating elements that automatically follow downstream water-level fluctuations while remaining mechanically constrained to preserve turbine alignment with the issuing water jet. This semi-constrained floating configuration enables efficient energy extraction while avoiding extensive civil construction and minimizing environmental disturbance.

3.3 Floating Platform Design

The floating platform was designed to provide sufficient buoyancy to support the turbine, shaft, bearings, and transmission system while maintaining stable hydraulic operation. The floating body consists of corrosion-resistant hollow steel box sections filled with lightweight foam to ensure adequate buoyancy and long-term durability. Bearings supporting the turbine shaft are mounted directly on the floating structure, while guide rods positioned at both ends permit only controlled

vertical movement inside the steel chassis. The buoyancy requirements were determined according to Archimedes' principle:

$$Fb = \rho \cdot V_{im} \cdot g \qquad (1)$$

where F_b is the buoyancy force (N), ρ is water density (kg m^{-3}), V_{im} is the immersed volume (m^3), and g is gravitational acceleration (9.81 m s^{-2}). The total downward load acting on the floating platform consists of both the structural weight and the dynamic force generated by jet impact on the turbine; the floating dimensions were selected so that the resulting buoyancy force exceeded this total applied load while maintaining adequate freeboard for stable operation throughout the experimental program.



Floating Platform

3.4 Cross-Flow Turbine

The cross-flow turbine was selected for its high hydraulic efficiency at low head, simple and economical fabrication from locally available materials, low maintenance requirements, and tolerance to debris - properties well suited to decentralized hydropower recovery from irrigation canals and barrage outflows. Compared with reaction turbines, it offers stable performance over a relatively wide range of discharge conditions and compatibility with existing barrage structures without structural modification. Its initial configuration consisted of eight straight blades, 40 cm in length and 5 cm in height, mounted on a 10 cm diameter hub carried on a 1.2 cm diameter shaft supported by the floating body; this geometry was later revised, as described in Section 4.5.



Cross-Flow Turbine

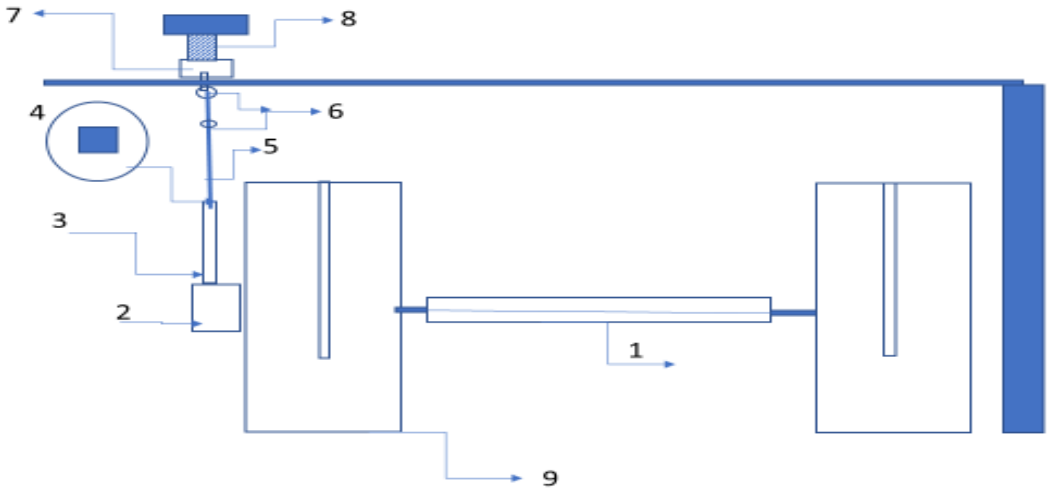
3.5 Steel Guiding Chassis and Motion Transmission

A rigid steel chassis, approximately 60 cm in length and 11 cm in width, was developed to guide the floating platform and prevent undesirable movement. Unlike a completely free-floating system, the chassis permits only vertical displacement while preventing excessive surge, sway, pitch, and roll. The guiding mechanism consists of vertical rails 35 cm in height installed on both sides of the chassis, allowing the floating body to move smoothly in response to water-level fluctuations, while the lower part of the chassis forms a confined water chamber that stabilizes the floating body and minimizes oscillatory motion generated by the water jet.



Steel Guiding Chassis

Mechanical power generated by the turbine is transmitted to a torque meter through a specially designed mechanism consisting of the turbine shaft, a bevel gearbox (velocity ratio 1:3), a hollow cylindrical tube, a sliding square shaft, two hinged joints, and supporting bearings. This arrangement combines mechanical flexibility with reliable torque transfer, allowing the drivetrain to accommodate the platform's vertical travel without binding, representing one of the practical engineering solutions that make the floating, self-adjusting concept workable.



Transmission motion mechanism, 1). Cross flow turbine, 2). Gear box with velocity ratio1:3, 3). hollow cylindrical tube, 4). Ring of square hollow, 5). Bar of square cross-section, 6). Two hinges, 7). Two bearings, 8). Torque meter, 9). chasses

4. Design Optimization: The Adaptive Floating Mechanism

4.1 Design Evolution Overview

The system was developed through three successive experimental configurations (Fig. 2, Table 1), each addressing specific limitations identified in the configuration before it. This iterative approach isolates the contribution of each design element and demonstrates why the adaptive mechanism - the central innovation of this study - was necessary.



(I) (II) (III)

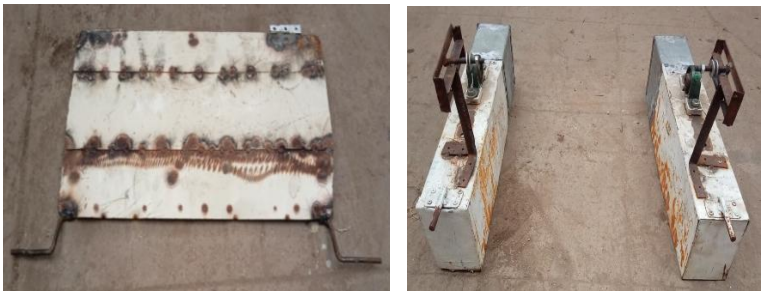
Fig. 2. Design evolution across the three experimental scenarios: (I) basic floating turbine, (II) adjustable guiding vane, (III) adaptive lever mechanism.

4.2 Scenario I: Basic Floating Turbine

The first configuration placed a floating cross-flow turbine downstream of the barrage gate with no flow-guiding device; the turbine's position was controlled solely by buoyancy. This confirmed the basic feasibility of extracting energy from the outflow, but only about half of the water jet interacted with the blades - the remainder bypassed the runner. Dynamic loading from the jet also produced excessive oscillation of the floating body, which misaligned the runner with the jet and reduced both rotational speed and power output.

4.3 Scenario II: Jet-Guidance Optimization

To improve jet capture, an articulated guiding vane was installed at the downstream edge of the gate, connected to the floating structure through hinged supports so its inclination could change with water level. This produced a more uniform jet distribution across the turbine width, better jet-runner alignment, and reduced dispersion losses. However, the guiding vane responded passively to buoyancy alone and still could not fully compensate for large or rapid water-level swings - the platform's adaptation remained insufficient under these conditions.



Guidance Vane & it's supporting on the floating body

4.4 Scenario III: The Adaptive Lever Mechanism

The third configuration introduced the principal innovation of this study: a two-arm lever mechanically linking the floating platform to the guiding vane (Fig. 3). The lever's shorter arm attaches to the vane; its longer arm connects to the floating body. As the downstream water level rises, buoyancy lifts the floating body, and the lever simultaneously rotates the vane downward, shortening the jet trajectory so that it continues to strike the turbine near the optimum point. When the water level falls, the platform descends and the lever rotates the vane upward, extending the trajectory to compensate. This passive

mechanical coupling - requiring no sensors, electrical actuators, or external control - kept the turbine aligned with the jet across the full range of water levels tested, and represents the central engineering contribution of this paper.

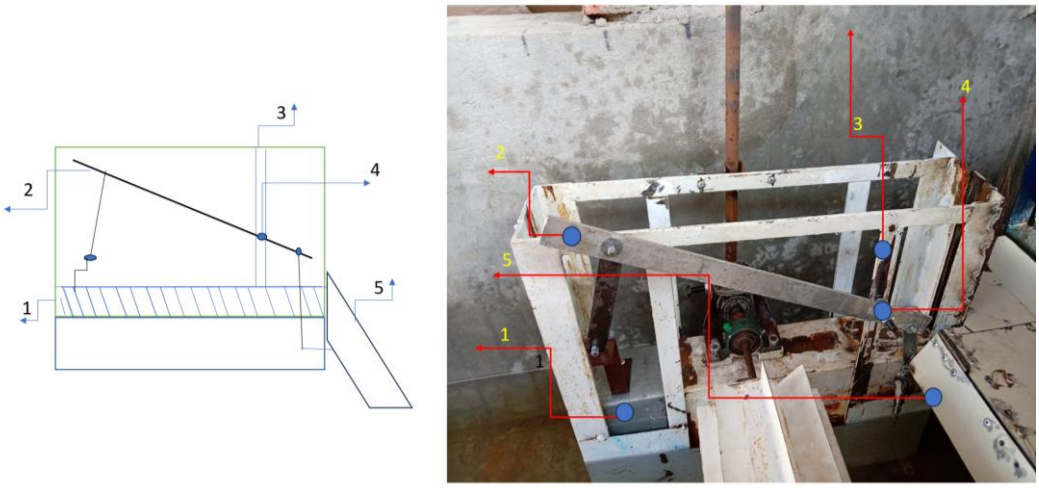


Fig. 3. The adaptive lever mechanism: (left) schematic showing float body (1), lever arm (2), chassis (3), pivot (4), and guiding vane (5); (right) corresponding components on the physical model.

4.5 Turbine Runner Optimization

Following adoption of the adaptive mechanism, the turbine runner itself was redesigned (Fig. 4): blades were lengthened and bent to an angle of approximately 55°, and circular end plates were added on both sides. These changes reduced lateral leakage around the blade tips, improved jet confinement, and increased momentum transfer between the jet and the runner, producing smoother rotation and greater mechanical stability across both low- and high-head conditions.



Fig. 4. The redesigned cross-flow turbine runner with lengthened, curved blades and end plates, installed in the guide chassis.

4.6 Synthesis and Novel Engineering Contribution

The three-stage optimization process illustrates the progressive development of the proposed floating hydropower system. The initial configuration demonstrated the technical feasibility of energy extraction from barrage outflows but suffered from poor hydraulic utilization and platform instability.

The second configuration substantially improved flow distribution through the introduction of an articulated guiding vane. Finally, the adaptive lever mechanism provided automatic compensation for variations in downstream water level, enabling continuous alignment between the jet and the turbine, while the subsequent redesign of the runner geometry further increased hydraulic efficiency by improving jet confinement and blade loading.

The optimization procedure resulted in several distinct engineering innovations: a passive self-adjusting control mechanism requiring no external power; automatic regulation of jet trajectory as downstream water level changes; continuous turbine alignment maintained without sensors, electrical actuators, or automated control systems; improved hydraulic efficiency achieved through optimized runner geometry; and enhanced operational stability provided by a semi-constrained floating support system. Together, these features distinguish the proposed system from previously reported floating hydropower technologies and represent the principal engineering contribution of this study.

Table 1 summarizes the three configurations. The progression demonstrates that jet guidance alone (Scenario II) improves flow distribution but cannot compensate for changing water levels; only the addition of a mechanical feedback path between platform motion and vane angle (Scenario III) closes that gap. Combined with the redesigned runner, this configuration produced the highest and most stable efficiency of the three, and is the configuration used for the full-scale projections in Section 6.

Table 1. Comparison of the three design scenarios.

Scenario	Main Modification	Problem Addressed	Improvement Achieved
I	Basic floating turbine	Feasibility demonstration	Baseline performance
II	Adjustable guiding vane	Poor jet distribution	Improved jet alignment
III	Adaptive lever + redesigned blades	Water-level fluctuations	Automatic alignment; highest efficiency

5. Experimental Measurements

5.1 Hydraulic Parameters

For each experimental run, gate opening and discharge were adjusted to establish the required hydraulic condition; after the flow stabilized, upstream and downstream water levels, gate opening, discharge, jet velocity, turbine rotational speed, torque, and output power were recorded. Discharge through the orifice gate was calculated using the standard orifice equation:

$$Q = C_d \cdot Ao \cdot \sqrt{(2gH)} \quad (2)$$

where Q is discharge ($m^3\ s^{-1}$), Cd is the discharge coefficient (0.6-0.7), Ao = a·b is the orifice area (m^2), g is gravitational acceleration, and H is the head difference between the upstream water level and the gate opening. Two operating conditions were tested: a high-discharge condition (Cd = 0.7, gate opening a = 7.5 cm, H = 0.23 m, Q ≈ 100 L/s) and a low-discharge condition (a = 5.5 cm, H = 0.085 m, Q ≈ 44.7 L/s); the gate width b was 0.9 m in both cases.

The horizontal distance travelled by the jet, x, was estimated from Bernoulli's equation combined with projectile motion:

$$x = Cv \cdot 2\sqrt{(Hh)} \quad (3)$$

where Cv is the velocity coefficient (0.95-0.99) and h is the vertical distance between the jet centerline and the point of impact. This relationship governs how the adaptive lever mechanism (Section 4.4) must reposition the guiding vane as water level changes, since h - and therefore x - depends directly on platform position. Under the high-discharge condition tested, the jet travelled approximately 19.3 cm before striking the turbine; under the low-discharge condition, this distance increased to approximately 23.4 cm. This roughly 4 cm shift in impact point is precisely the trajectory change that the adaptive lever mechanism must - and, per the results in Section 6, does - compensate for automatically as gate operating conditions vary.

5.2 Power and Efficiency

Hydraulic power available in the jet, mechanical power delivered by the turbine, and overall efficiency were computed as:

$$Phyd = \eta \cdot \rho \cdot g \cdot Q \cdot H \quad (4) \qquad Pout = T \cdot \omega,\ \omega = 2\pi N/60 \quad (5) \qquad \eta = (Pout / Phyd) \times 100 \quad (6)$$

Measured efficiency of the laboratory-scale prototype ranged from approximately 1% to 26% depending on applied load and discharge condition (Section 6). The upper end of this range is well below typical full-scale cross-flow turbine efficiency; this is expected at model scale, since the physical model operates at a substantially lower Reynolds number than the projected full-scale prototype (Table 3), and such scale effects are a well-known limitation of small hydraulic models rather than an indication of the turbine's design efficiency.

Nomenclature: Q, discharge ($m^3\ s^{-1}$); H, head (m); η, efficiency; P_{out}, measured mechanical power (W); P_{hyd}, hydraulic power (W); T, torque (N·m); N, rotational speed (rpm); ω, angular velocity (rad s^{-1}); F_b, buoyancy force (N); ρ, water density (kg m^{-3}); x, jet horizontal distance (m); C_d, C_v, discharge/velocity coefficients.

6. Results and Discussion

6.1 Effect of the Design Evolution on Performance

Measured performance improved consistently across the three scenarios described in Section 4. The basic floating configuration (Scenario I) confirmed technical feasibility but suffered substantial hydraulic losses from incomplete jet capture and platform oscillation. The guiding vane (Scenario II) improved jet distribution and alignment but could not fully compensate for water-level changes. The adaptive lever mechanism (Scenario III), combined with the redesigned runner, produced the best and most consistent performance of the three: it maintained turbine alignment automatically across the tested range of downstream water levels, without external sensors or actuators.

6.2 Influence of Water-Level Variation

One of the principal objectives of the proposed system was to compensate automatically for changes in downstream water level. Experimental observations demonstrated that the adaptive linkage successfully maintained turbine alignment over the tested operating range: as the water level rose, the floating body lifted and the lever mechanism rotated the guiding vane to shorten the jet trajectory, keeping the point of impact close to the optimum position on the runner. Conversely, when the downstream water level decreased, the floating body descended and the guiding vane automatically

extended the jet trajectory, again preserving alignment. This passive adjustment substantially reduced the performance losses commonly associated with conventional floating hydropower systems, which typically rely on buoyancy alone.

The optimized turbine runner also exhibited noticeably improved hydraulic behavior relative to the original configuration. Increasing the blade length and introducing end plates reduced water leakage around the runner while increasing momentum transfer from the water jet to the blades, resulting in smoother turbine rotation and greater mechanical stability. The experiments further demonstrated that the semi-constrained floating support effectively suppressed excessive oscillation of the platform while still preserving sufficient freedom of motion for the adaptive mechanism to operate.

6.3 Power and Efficiency

Table 2 summarizes measured turbine power and efficiency at representative loads for the two discharge conditions tested; the complete dataset is provided in Supplementary Table S1. Efficiency peaked at approximately 26% under the low-discharge condition and approximately 15% under the high-discharge condition, in both cases near the lower end of the applied load range, and declined at higher loads - a pattern consistent with the torque-speed characteristics typical of cross-flow turbines.

Table 2. Measured turbine power and efficiency (representative loads; full dataset in Supplementary Table S1).

Discharge Condition	Load (g)	Speed N (rpm)	Torque (N·m)	Power Pm (W)	Efficiency η (%)
Low (≈44.7 L/s)	50	102	0.485	5.18	14.9
Low (≈44.7 L/s)	150	69	0.485	3.50	10.1
Low (≈44.7 L/s)	300	26	0.460	1.25	3.6
Low (≈44.7 L/s)	500	8	0.460	0.39	1.1
High (≈100 L/s)	50	65	0.425	2.89	26.2
High (≈100 L/s)	150	48	0.445	2.24	20.3
High (≈100 L/s)	300	34	0.455	1.62	14.7
High (≈100 L/s)	450	0	0.420	0.00	0.0

The gap between the model-scale efficiencies above and typical full-scale cross-flow turbine efficiencies (Table 3) is attributable to scale effects: the physical model operates at a Reynolds number roughly one order of magnitude below the projected full-scale barrage installation, where the reduced relative influence of viscous losses is expected to substantially improve efficiency.

Table 3. Efficiency and Reynolds number: model versus projected full-scale (barrage) system.

System	Q (m^3/s)	Re	Velocity (m/s)	Efficiency
Model (1:9 scale)	0.0447-0.1	(2-4.5) $\times 10^5$	0.73-1.62	15-26%
Full-scale (barrage)	10.9-24.3	(1.4-3) $\times 10^6$	0.5-0.8	~ 40-70%

6.4 Energy Production Potential and Environmental Benefit

Extrapolating the measured performance to full scale (Table 4), each barrage gate equipped with the developed system is projected to generate approximately 51-91 MWh of electricity annually. Because barrages typically comprise multiple gates, the cumulative potential across a single barrage could be substantial. This generation would displace grid electricity and correspondingly reduce CO2 emissions by an estimated 30-53 t CO2 per gate per year (using a grid emission factor of 0.533 kg CO2/kWh), representing an environmental benefit of approximately USD (428-767) $ per gate annually at an assumed carbon price of $14.5/t CO2.

These figures are conservative in the sense that they are extrapolated directly from a single, non-optimized laboratory prototype; further refinement of the runner geometry and drivetrain efficiency (Section 7) would be expected to improve the full-scale yield. Even at the measured scale, however, the combination of negligible civil-works cost, compatibility with existing barrage infrastructure, and a passive control mechanism that requires no ongoing operational input makes the levelized cost of energy for this technology potentially competitive with other small-scale renewable options in regions - such as the Nile Delta - with a dense network of regulated irrigation and drainage structures. Egypt alone operates dozens of major barrages and thousands of smaller control gates, suggesting that the cumulative national potential of this class of technology, while not quantified in the present study, could be substantial.

Table 4. Projected annual energy production, CO2 mitigation, and environmental value per barrage gate.

Discharge (L/s)	Power Pm (W)	Prototype Power (kW)	Annual Energy (MWh/gate)	CO2 Mitigated (t/gate/yr)	Est. Value (USD/gate/yr)
100 (high)	2.891	6.324	51.0	~30	~428
44.7 (low)	5.178	11.324	91.3	~53	~767

7. Conclusions and Future Work

This study presented the design, development, and experimental validation of a floating-supported cross-flow turbine for recovering hydropower from low-head barrage outflows. A 1:9 physical model representing one orifice gate of Damietta Barrage was tested through three successive design configurations, isolating the contribution of each design element to overall performance. The principal findings are:

A floating-supported cross-flow turbine can recover renewable energy from barrage outflows without structural modification to existing infrastructure, at low construction cost. An adaptive mechanical lever linking the floating platform to a guiding vane automatically compensates for fluctuating downstream water levels, maintaining turbine-jet alignment without sensors or active control - the central innovation of this work. A semi-constrained floating support (steel chassis with vertical guide rails) substantially improves stability by restricting undesirable horizontal and rotational motion while preserving the vertical freedom the adaptive mechanism requires. Redesigning the turbine runner with longer, curved blades and end plates improved momentum transfer and hydraulic confinement, raising efficiency beyond that achieved by the adaptive mechanism alone. Full-scale projections indicate 51-

91 MWh of electricity and 30-53 t CO2 mitigation per gate annually, at low incremental infrastructure cost.

Because the system requires no major civil works and can be retrofitted to existing hydraulic structures, it offers a practical, scalable pathway for distributed renewable-energy generation from regulated waterways.

Future work should prioritize: (1) long-term field trials at full scale to assess durability, reliability, and maintenance requirements under real operating conditions; (2) CFD-based optimization of the turbine runner geometry to improve energy-conversion efficiency; and (3) environmental impact assessment to evaluate potential interactions with sediment transport, aquatic ecosystems, and navigation, together with an assessment of system vibration effects on the existing barrage structure.

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