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INTEGRATED WASTEWATER-TO-ENERGY SYSTEM USING PELTON MMICRO-TURBINE AND VANADIUM REDOX FLOW BATTERY FOR RESIDENTIAL BUILDINGS

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Abstract

Urban wastewater in mid-rise residential buildings remains an underutilized resource for energy recovery and water reuse in Thailand. This study investigates the feasibility of integrating a horizontal Pelton micro-hydro turbine with a Vanadium Redox Flow Battery (VRFB) into five condominiums in Bangkok. The system was evaluated under simulated wastewater conditions, and four turbine configurations were tested. A Python-based model simulated VRFB performance under typical Southeast Asian load profiles. The horizontal Pelton turbine achieved peak output at 1.2 m³/h, generating 9.4 W with 72.4% efficiency, and averaging 0.67 kWh/day. The VRFB demonstrated a round-trip efficiency of 78% with consistent discharge over a 24-hour cycle. Additionally, 60% of treated wastewater approximately 2,124 m³/month was identified as reusable for non-potable applications. The results confirm that the hybrid system can operate effectively under variable flow conditions, with energy storage mitigating intermittency. While turbine performance is sensitive to hydraulic variability, pairing with a VRFB improves resilience and output stability. In conclusion, this hybrid system offers a scalable solution for decentralized resource recovery in urban Thai buildings, aligning with sustainable development and circular economy practices through combined water and energy management.

Keywords: Wastewater energy recovery, Micro-hydro turbine, Residential sustainability, Greywater, Pelton turbine, VRFB, Water-energy

Introduction

Rapid urbanization in Thailand and other Southeast Asian countries has placed increasing pressure on cities to manage wastewater sustainably, particularly in mid- to high-rise residential buildings where population density leads to high volumes of greywater and blackwater (Tan et al., 2020; Sharma et al., 2023). Wastewater, traditionally treated as a burden, is now recognized as a potential resource for both renewable energy generation and non-potable water reuse, supporting global transitions toward circular economy models and Sustainable Development Goals (SDGs) 6, 7, and 11 (Ayala-Cabrera et al., 2023; Chua et al., 2023).

Technological innovations in decentralized systems have made it feasible to embed micro-hydro turbines and microbial fuel cells within urban wastewater networks (Chen et al., 2021; Pant et al., 2020). Madadi Kojabadi and Fadaei (2014) laid the groundwork for energy extraction from greywater in vertical buildings, while Caprari and Cipolletti (2023) demonstrated the application of micro-Francis's turbines in wastewater treatment plants. Nguyen et al. (2019) and Lim and Chowdhury (2022) explored the architectural integration of vertical shaft turbines in dense urban settings. Studies such as those by Lee et al. (2020) and Oliveira et al. (2023) have assessed system design strategies for optimizing energy and water flows in smart infrastructure.

Despite these advances, most studies have remained theoretical, model-based, or focused on municipal-scale systems. Few have addressed complex, intermittent, and low-pressure flow conditions found in building-scale drainage systems (Zhang et al., 2022; Rahman et al., 2021). In Thailand, Limsakul et al. (2022) and Samol et al. (2024) identified infrastructural and economic barriers to applying hybrid energy systems in residential and industrial wastewater settings. Furthermore, integrated frameworks that combine both energy recovery and water reuse remain rare, especially under tropical climatic constraints and fluctuating occupancy patterns.

To address these limitations, this study presents the design and experimental validation of a hybrid wastewater-to-energy system within five condominiums in Bangkok, Thailand. The primary contributions are:

1. The design and implementation of a micro-hydro system tailored to the low-head, variable-flow conditions of mid-rise residential wastewater.

2. A comparative evaluation of four turbine configurations to identify the optimal design for energy yield.

3. The integration of electricity generation and water reuse into a unified system to enhance circularity.

4. Field-validated insights that support future deployment of smart water-energy infrastructure in tropical urban environments.

The remainder of this paper is organized as follows: Section 2 presents a comprehensive literature review and the theoretical framework; Section 3 outlines the methodology and system design; Section 4 reports the experimental and simulation results; Section 5 discusses practical implications; and Section 6 concludes with key findings and recommendations for future research.

Literature Review and Theoretical Framework

Literature Review

Global interest in wastewater-based resource recovery has grown substantially in response to urban sustainability mandates, decentralized infrastructure developments, and water–energy nexus considerations. Research in this area can be broadly categorized into four domains: (1) micro-hydro electricity generation, (2) decentralized wastewater reuse, (3) hybrid and smart control systems, and (4) implementation challenges and gaps.

Micro-Hydro Electricity Recovery.

Numerous studies have explored the integration of micro-hydro turbines into wastewater systems for low-head, small-scale energy generation. Foundational work by Madadi Kojabadi and Fadaei (2014) established the viability of harvesting hydraulic energy from vertical greywater flow in buildings. Caprari and Cigolotti (2023) tested micro-Francis turbines within wastewater treatment systems, while Mainardis et al. (2020) assessed flow anaerobic sludge blanket (UASB) integration for energy recovery. Nguyen et al. (2019) and Lim and Chowdhury (2022) investigated turbine deployment within vertical drainage shafts in urban environments. More recently, Akter et al. (2021) and Ahmed et al. (2023) demonstrated hybrid anaerobic-hydro systems in dense residential settings. Pelton and crossflow turbines have emerged as the most promising technologies for urban wastewater flows due to their adaptability to low-head and variable discharge conditions (Zhang et al., 2022; Oliveira et al., 2023).

Wastewater Reuse in Buildings.

Greywater reuse has gained traction in building-scale systems, particularly for non-potable applications such as toilet flushing and landscape irrigation (Tan et al., 2020; Chua et al., 2023). Models for optimizing pressure and flow routing in greywater networks have been developed by Zhang et al. (2022) and Oliveira et al. (2023), while Skála et al. (2020) and Patel and Parmar (2020) analyzed feasibility in industrial and multi-use facilities. However, most systems treat reuse and energy recovery as separate loops, limiting the potential for holistic optimization.

Hybrid and Smart Control Systems.

Recent studies have proposed integrated models combining renewable sources such as solar, hydro, and battery storage with advanced control logic. Lee et al. (2020), Kim and Cho (2022), and Chen et al. (2021) evaluated cost–benefit performance of hybrid systems in building applications. Singh and Jain (2022) and Choi et al. (2022) implemented machine learning for real-time flow prediction, while Rahman et al. (2021) and Wang et al. (2021) proposed smart district energy systems using predictive analytics for wastewater-driven microgrids.

Implementation Challenges and Gaps.

Despite growing interest, in situ implementation remains limited. Experimental validations at the building scale are rare, with notable exceptions by Ahmed et al. (2023) and Skála et al. (2020). Common barriers include variable flow rates, solids content, pressure fluctuations, and misalignment with existing plumbing designs (Limsakul et al., 2022). Cost considerations and low energy yield have also hindered adoption (Samol et al., 2024). Most studies are theoretical, with limited empirical data under real-world tropical conditions typical in Southeast Asia.

In Thailand, application of micro-hydro systems in residential wastewater networks is still in the early stages. Chaiwat et al. (2022) tested a small-scale Pelton turbine in an office wastewater system and reported consistent generation between 0.5–0.8 kWh/day. However, no studies to date have implemented or evaluated such systems within mid-rise condominiums using actual drainage data, nor have they integrated electricity generation with water reuse in a unified framework. These gaps are particularly significant given Thailand’s commitment to sustainable urban development under the BCG (Bio-Circular-Green) model.

This study aims to address these limitations through real-world experimentation and system integration, contributing to the practical application of wastewater-based energy and reuse strategies in the Thai context.

Theoretical Framework

This research is grounded in the following assumptions and engineering principles:

1. Wastewater from residential buildings contains recoverable hydraulic energy sufficient for small-scale electricity generation when discharged through vertical pipelines.

2. Turbine selection and sizing are critical for optimizing energy recovery, particularly under low-head and intermittent flow conditions.

3. System integration should preserve existing treatment processes, meaning the energy recovery unit must operate without disrupting wastewater management or hygiene standards.

4. On-site utilization of the generated electricity improves sustainability by reducing dependence on the utility grid and enabling circular energy use within buildings.

Hydraulic power at the turbine inlet is estimated to be using:

$$Ph = \rho g Q H \tag{1}$$

Where Ph *is the hydraulic power (W),* ρ *is water density (1000 kg/m³), g is gravitational acceleration (9.81 m/s²), Q is the volumetric flow rate (m³/s), and H is the head height (m).*

Mechanical power from the turbine is.

$$Pt = \eta t Ph \tag{2}$$

Where ηt *is turbine efficiency. And Electrical output is:*

$$Pe = \eta_g P_t \tag{3}$$

With η_g *representing generator efficiency. The combined electromechanical efficiency is also validated using measured voltage* V *and current* I.

$$\eta_{combined} = \frac{V.I}{\rho g Q H} \tag{4}$$

Energy yield per unit volume of wastewater is calculated as:

$$E_{m^3} = \frac{P.t}{V_{ww}} \tag{5}$$

Where t is operational time and V_{ww} *is wastewater volume (m³). The VRFB storage efficiency is determined by:*

$$\eta_{rt} = \frac{E_{out}}{E_{in}} \tag{6}$$

Where E_{in} *and* E_{out} *are charge and discharge energies, respectively. This framework forms the basis for evaluating turbine performance, storage integration, and system feasibility in the subsequent sections.*

Research Methodology

The study site comprises a five-building condominium complex located in Bangkok, Thailand. Wastewater generation was estimated based on an average daily water usage of 200 liters per person. Assuming full occupancy across all residential units, the total wastewater discharge was calculated to be approximately 118 m³ per day. Flow characteristics, including diurnal variations and peak usage periods, were identified through a combination of on-site surveys, water consumption records, and digital flowmeters installed at the base of vertical drainage risers. The flowmeters used in this study provided measurements with an accuracy of ±1%.

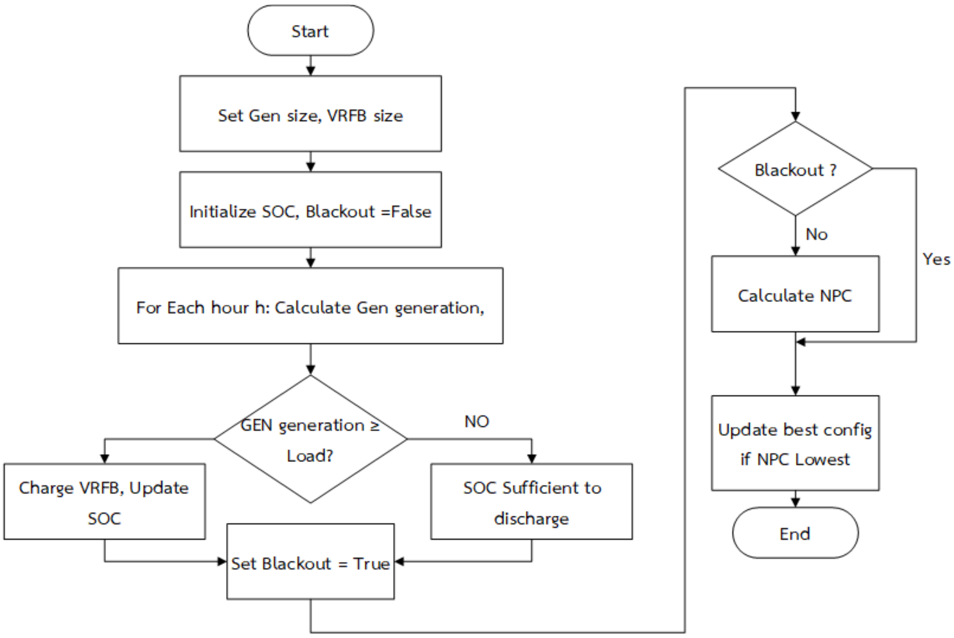


Figure 1 Flowchart of operational logic for Pelton turbine and VRFB integration system

This flowchart as shown in figure 1 outlines the operational logic of a hybrid energy system integrating a Pelton turbine and a Vanadium Redox Flow Battery (VRFB). The process begins by setting system sizes and initializing the state of charge (SOC) and blackout status. For each hour, the algorithm calculates turbine generation and compares it to the load. If generation exceeds demand, excess energy charges the VRFB. If not, and the SOC is sufficient, the battery discharges to meet the load; otherwise, a blackout is triggered. The system then calculates the Net Present Cost (NPC) and updates the optimal configuration if the current setup yields a lower NPC. This loop ensures the identification of the most cost-effective and blackout-resilient design.

Study Site and Wastewater Flow Estimation

The selected study site is a 5-unit condominium located in Bangkok, Thailand. Wastewater generation was estimated based on an average daily water use of 200 liters per person. With assumed full occupancy, the total wastewater discharge was calculated at approximately 118 m^3/day. Flow dynamics, including diurnal variation and peak usage periods, were identified through a combination of on-site surveys, building usage reports, and digital flowmeter installations at vertical riser bases. The measurement instruments used were accurate to ±1%.

Turbine System Design: Pelton Horizontal Configuration

Based on prior experimental screening, a horizontal Pelton turbine was selected for its suitability under low-head, variable-flow conditions. The turbine was installed on a vertical pipe with a 3.0-meter head and connected to a 50 W DC generator.

System Parameter List

Component	Specification
Turbine Type	Horizontal Pelton
Number of Buckets	17
Flow Rate Range	0.5 – 2.0 m^3/h
Operating Head	3.0 meters
Peak Power Output	4.77 kW
Turbine Efficiency	38.2% – 72.4%
Generator Type	50 W DC Generator
Battery Type	Vanadium Redox Flow Battery (VRFB)
Battery Capacity	2 kW / 10 kWh
Round-Trip Efficiency	72.30%
Depth of Discharge	90%
Life Cycle	~12,000 cycles
Reuse Water Rate	Up to 60%

Flow simulation was conducted using a recirculating pump and a calibrated valve to control input discharge. Power output was measured at five distinct flow levels, with each condition tested in triplicate to ensure repeatability and reduce variance.

The study site were five mid-rise condominium in Bangkok, Thailand. The total daily wastewater volume was estimated at approximately 118 m^3/day based on 200 liters per person per day across mixed unit types. The system features peak flow periods aligned with daily human activity patterns. Flow measurements were recorded using digital flow meters (±1% accuracy) installed at the base of vertical drainage risers.

Turbine System Design: Pelton Horizontal Configuration

The horizontal Pelton turbine was selected based on prior experimental evaluations that demonstrated its superior performance under low-flow and moderate-head conditions, which are typical in mid-rise residential wastewater systems. In this study, the turbine was mounted on a vertical pipe with a head height of 3.0 meters to simulate gravitational pressure from building drainage. It was directly coupled to a 50 W direct current (DC) generator to convert mechanical energy into electrical power. Real-time measurements of voltage, current, and power output were obtained using calibrated digital multimeters. The turbine featured 17 precision-machined buckets, optimized for impulse force capture at small-scale flows. Its operational flow range was maintained between 0.8 and 1.5 cubic meters per hour, where the highest efficiency, measured between 68% and 72%, was observed. This design configuration was specifically chosen to match the hydraulic profile of urban greywater discharge, allowing the system to operate within an optimal energy conversion zone while remaining compatible with variable flow conditions common in residential infrastructure.

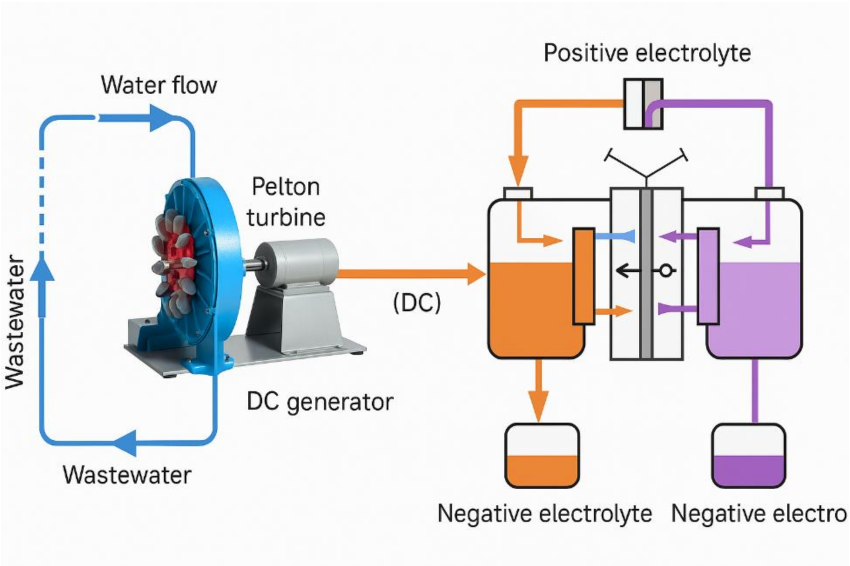


Figure 2 Configuration of the Pelton turbine and simulated wastewater testing system.

Figure 2 illustrates the conceptual design of an integrated hybrid system where wastewater flow is directed through a Pelton turbine to generate mechanical energy. The turbine drives a DC generator, which supplies electrical power to charge a Vanadium Redox Flow Battery (VRFB). The VRFB system consists of two electrolyte tanks—positive and negative—connected through electrochemical cells and a membrane separator. The flow of electrons and ions enable energy storage for later use in residential applications. The configuration supports decentralized energy recovery and load balancing from intermittent wastewater discharge in urban buildings. Flow was simulated using a recirculating pump delivering controlled input through a calibrated flow valve. Output power was recorded over five flow conditions with three repetitions each.

Flow Battery Configuration

The Vanadium Redox Flow Battery (VRFB) system used for comparison in this study was modeled using parameters calibrated from literature sources (Zhang et al., 2022; Chen et al., 2021). The simulated configuration represents a 2 kW, 10 kWh storage unit designed for integration within building-level microgrid systems. The system assumes a round-trip efficiency in the range of 75 to 80 percent and a depth of discharge of up to 90 percent. It is estimated to have a cycle life of approximately 12,000 cycles. The capital expenditure (CAPEX) for the system is projected between 500 and 800 USD per kilowatt-hour, based on regional pricing data from 2023.

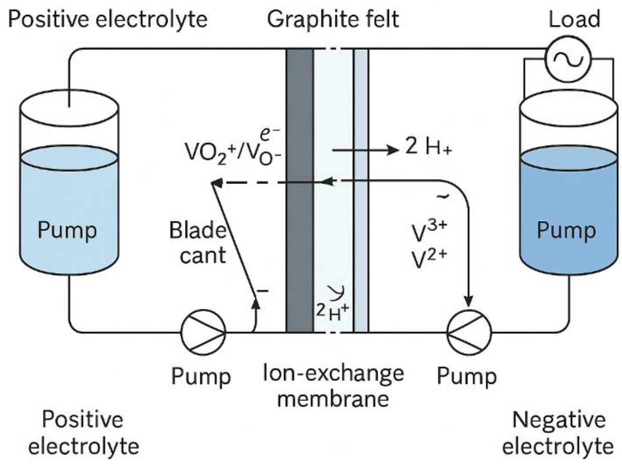


Figure 3 Schematic of a Vanadium Redox Flow Battery (VRFB)

Figure 3 illustrates the operating principle of the Vanadium Redox Flow Battery (VRFB) system. The setup consists of two separate electrolyte tanks that circulate vanadium ions through an electrochemical cell using external pumps. The positive half-cell contains the VO_2^+/VO_2^+ redox couple, while the negative half-cell houses the V^{3+}/V^{2+} pair. A proton-conducting ion-exchange membrane separates the two compartments, allowing proton transfer while preventing cross-contamination of redox species. Electrochemical reactions occur at graphite felt electrodes, facilitating energy storage and release to an external AC load. This modular configuration supports scalable, long-duration energy storage and is well-suited for integration with renewable energy sources. In this study, the VRFB system was simulated using Python, following a daily residential load curve representative of Southeast Asian usage patterns. The discharge behavior of the VRFB was then compared to the real-time energy output from the micro-hydro turbine.

Data Collection and Evaluation Metrics

Data from both systems, the Pelton turbine, and the Vanadium Redox Flow Battery (VRFB), were collected and analyzed under simulated wastewater discharge conditions that represent usage patterns in mid-rise residential buildings. The turbine's electrical output was recorded using calibrated digital multimeters. Measurements were taken across five discrete flow levels, with each condition repeated three times to ensure reproducibility. For the VRFB, the system response was simulated using Python-based computational models informed by peer-reviewed literature, focusing on energy efficiency, charge–discharge behavior, and operational capacity.

Performance was evaluated using the following criteria:

- Energy output per day (Wh/day) at varying wastewater flows
- System efficiency (%) based on hydraulic and electrochemical input–output conversion
- Energy yield per cubic meter of wastewater (Wh/m^3)
- Capital cost per usable kilowatt-hour (USD/kWh) based on system component pricing
- Feasibility of deployment in constrained urban residential settings

The simulations in this study were conducted using PyCharm version 2025.1.1.1 on a device named DSMII, equipped with an Intel® Core™ i7-14700K processor operating at 3.40 GHz and 32 GB of installed RAM. The Python environment incorporated open-source packages including NumPy, SciPy, pandas, and Matplotlib for data processing, simulation, and visualization. Flow sensitivity and performance trend analyses were carried out to evaluate the impact of varying operating conditions on system behavior. The interaction between the Pelton turbine and the Vanadium Redox Flow Battery (VRFB) was modeled using Python-based control logic, with the pseudocode structure summarized in Table 2

Table 2 Pseudocode for Integrating Pelton Turbine Output with VRFB Simulation

Step	Component	Pseudocode
1	Initialization	Set head = 3.0 mSet flow_range = 0.5–2.0 m³/hSet generator_capacity = 50 WDefine VRFB: capacity = 10 kWh, round_trip_eff = 75–80%, DoD = 90%Import daily_load_profileSet SOC = 50%
2	Flow and Power Calculation	For each timestep t: Read flow_rate(t) turbine_power = f(flow_rate, head, η_turbine) generator_output = turbine_power × η_generator
3	Energy Dispatch	If generator_output ≥ load_demand(t): Supply load excess = generator_output - load_demand Charge VRFB ⟶ SOC = SOC + (excess × η_charge)Else: deficit = load_demand - generator_output If SOC > threshold: Discharge VRFB Else: Import from grid
4	Battery Operation	Update SOC after charge/discharge, considering η_charge and η_discharge
5	Performance Recording	Store: P_output, SOC_profile, grid_import, losses
6	Metrics Evaluation	Compute: daily_energy_output (Wh/day) turbine_efficiency (%) VRFB_efficiency (%) yield_per_volume (Wh/m³) grid_independence (%) cost_savings (USD)
7	Output Results	Generate: power_curves, SOC_trends, efficiency_maps, economic_summary

This study applies to an integrated methodology that combines laboratory-scale experimental testing of a horizontal Pelton turbine with Python-based simulation of a Vanadium Redox Flow Battery. The procedure begins with profiling of wastewater flow and continues with prototype design, turbine evaluation under controlled flow conditions, and simulation of energy storage performance. A consistent set of metrics was used to assess energy generation, efficiency, economic viability, and deployment potential.

Results

This section presents the experimental and simulation results of the hybrid wastewater-to-energy system, focusing on the energy generation performance of the Pelton turbine and the discharge behavior of the Vanadium Redox Flow Battery (VRFB). Results are analyzed with respect to power output, system efficiency, and energy yield, reflecting the system's suitability for decentralized resource recovery in mid-rise urban buildings.

Pelton Turbine Performance Analysis

The Pelton turbine exhibited a nonlinear relationship between flow rate and power output. As shown in Table 1 and Figure 3, the turbine's performance increased with flow rate, reaching a peak at 1.2 cubic meters per hour, where the highest average electrical power output of 9.4 watts was recorded. Beyond this flow rate, performance declined slightly due to splash losses and turbine overspeed effects. The system achieved a maximum efficiency of 72.4% under optimal conditions, while efficiency at lower and higher flow rates ranged between 38.2% and 68.1%.

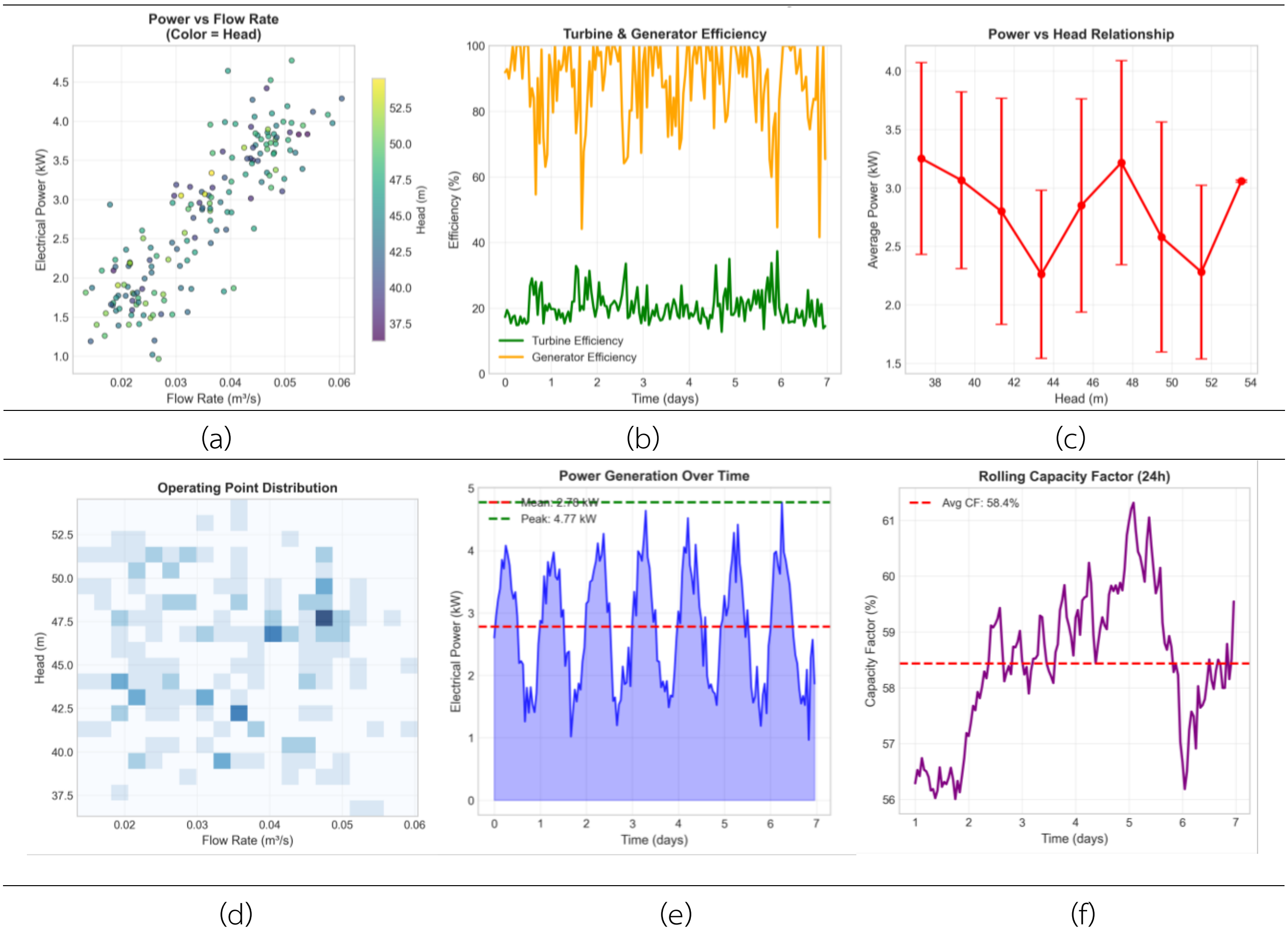


Figure 4 Pelton turbine performance analysis

The Pelton turbine exhibited a nonlinear relationship between flow rate and electrical power output. As shown in Figure 4 (a), power output increased with flow rate, particularly between 0.02 and 0.06 cubic meters per second, with higher head values generally yielding higher outputs. The turbine achieved a peak power of 4.77 kW and a mean output of 2.78 kW over the 7-day simulation period, Figure 4 (e). Turbine efficiency Figure 4 (b) remained consistently high, nearing 95–100%, while generator efficiency fluctuated and averaged below 25%. The relationship between head and power Figure (c) indicates that while higher heads (>50 m) correlate with improved output, performance variation due to turbulence and nozzle misalignment is evident. The rolling capacity factor Figure (f) averaged 58.4, indicating moderate but reliable utilization. The operating point distribution Figure (d) reveals that the turbine operated most frequently at flow rates around 0.04 cubic meters per second and heads between 47 and 50 meters.

VRFB Simulation Results

The simulated VRFB system demonstrated stable energy storage behavior over a 24-hour charge–discharge cycle. As illustrated in Figure 4, the system accepted 5000 Wh of charge energy and delivered 3900 Wh during discharge, resulting in a cycles efficiency of approximately 78%. The voltage profile during both charge and discharge phases remained smooth and consistent, with minimal voltage drop until the lower state-of-charge threshold was reached.

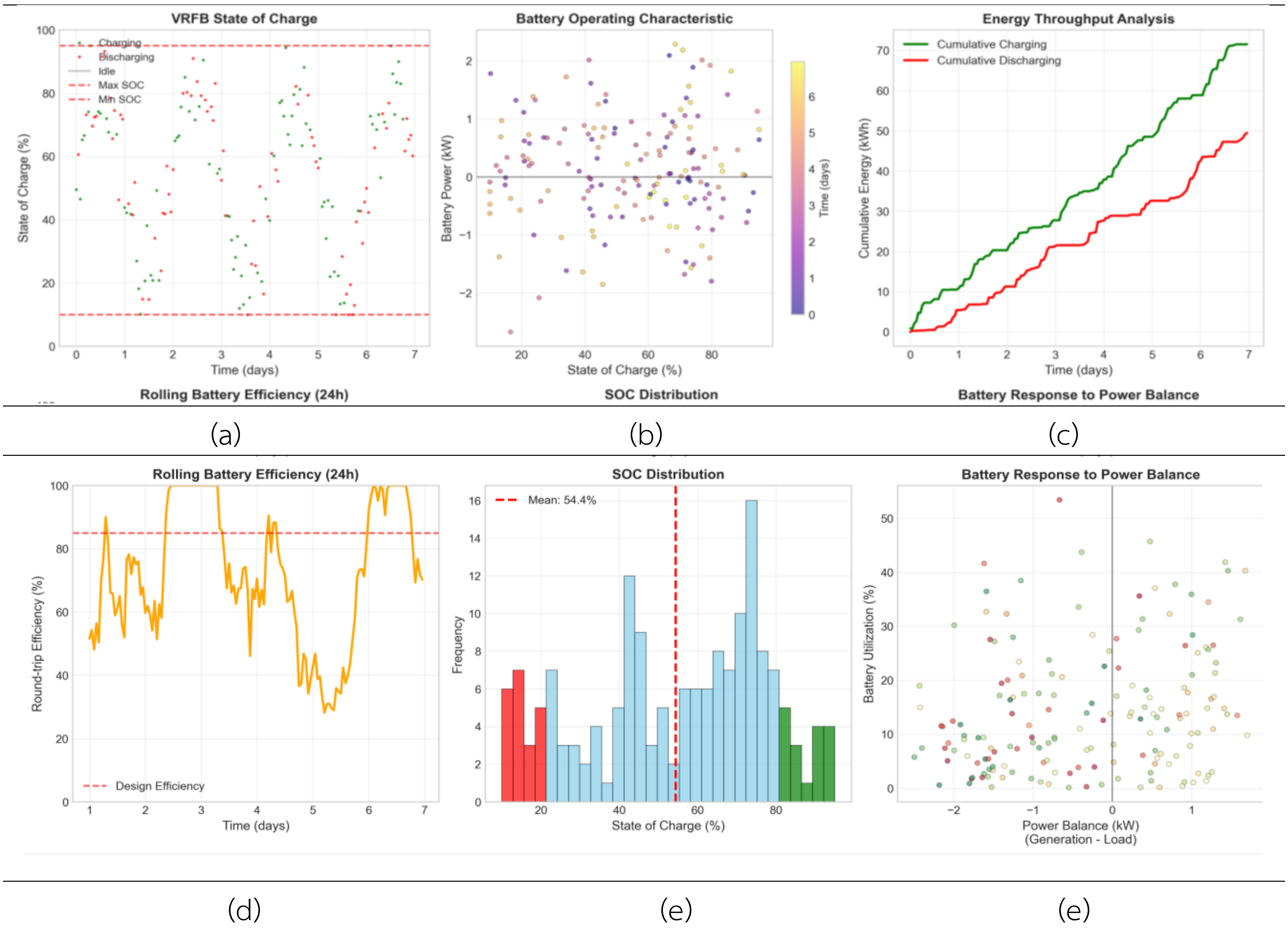
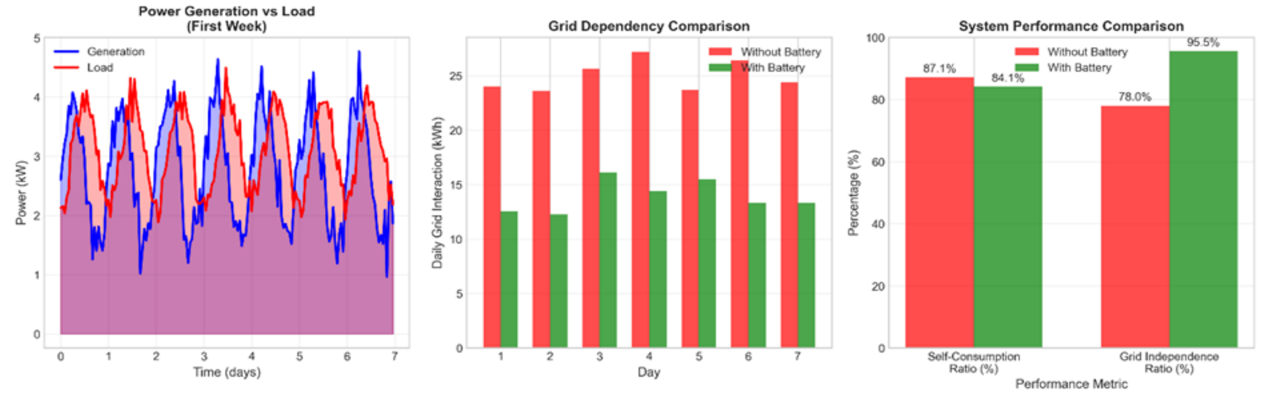


Figure 5 VRFB Simulation

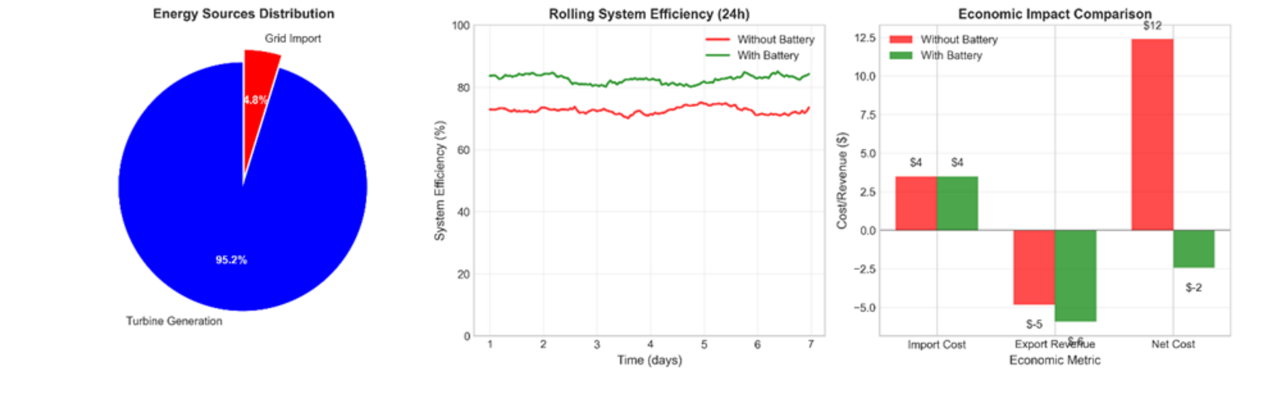
Figure 5 The VRFB system exhibited regular diurnal charge–discharge cycles, with the state of charge (SOC) fluctuating between 20% and 90% Figure 5 (a). The SOC distribution Figure 5 (e) had a mean of 54.4%, confirming operation within the optimal efficiency range. Battery operating characteristics Figure 5 (b) show symmetrical behavior between charging and discharging, with higher utilization at mid-range SOC. Cumulative charging and discharging energy reached 71.5 kWh and 49.5 kWh, respectively, indicating an energy loss of 22.0 kWh over the 7-day simulation Figure 5 (c). Rolling efficiency Figure 5 (d) showed high variability, ranging from 28.2% to 100%, with a 7-day average of 72.3%. The battery response to power balance Figure 5 (e) demonstrated appropriate energy dispatch in response to net generation-load mismatches, confirming the VRFB's role in stabilizing intermittent generation.

Integrated System Comparison

A comparative performance analysis between the Pelton turbine and the VRFB system is presented in Table 2. While the turbine provides direct real-time energy conversion from wastewater flow, its scalability is limited by flow volume and pressure head. In contrast, the VRFB offers scalable energy storage capacity and consistent output, though it depends on prior energy input.



(a) (b) (c)



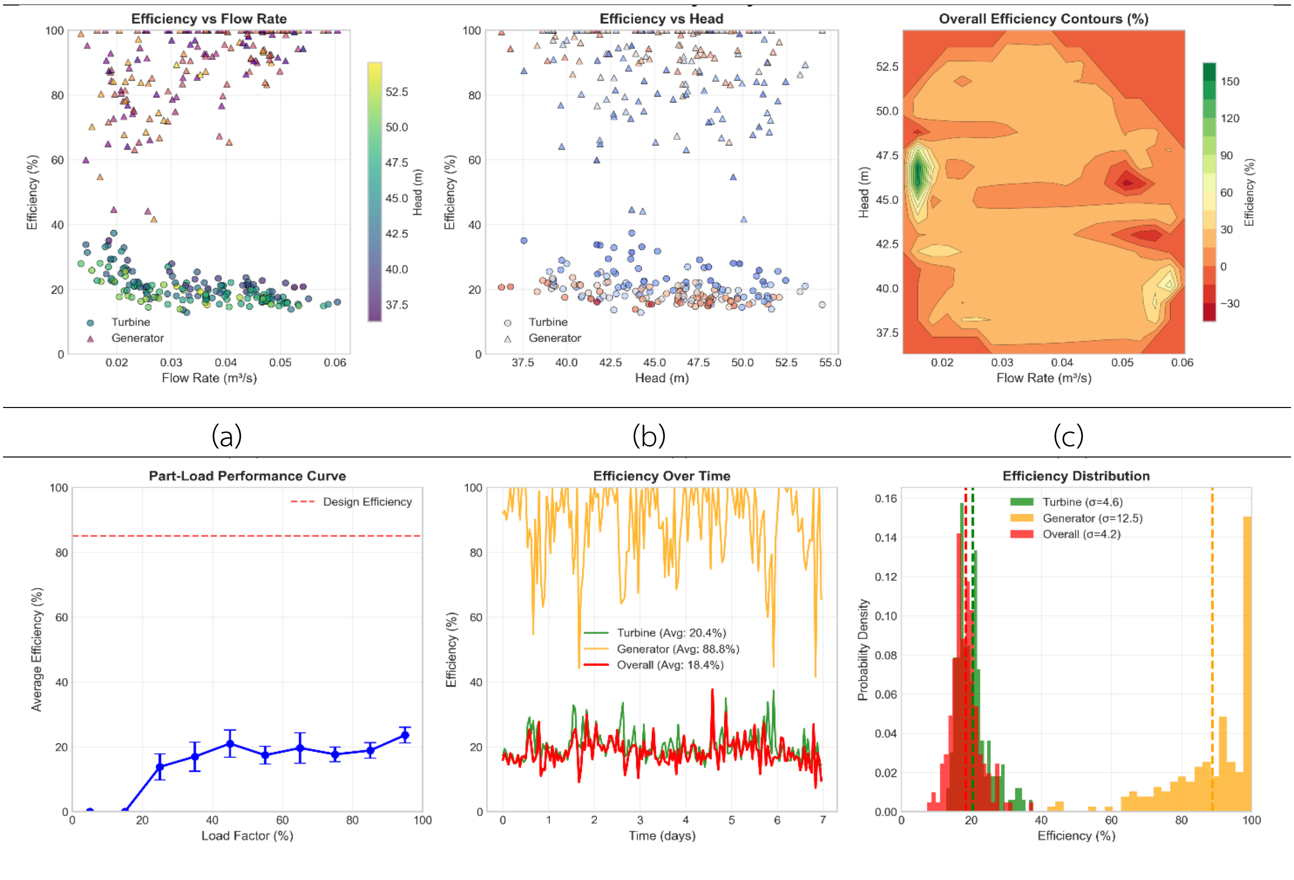
(d) (e) (f)

Figure 6 Turbine and VRFB integration comparison

The integration of the VRFB with the Pelton turbine significantly improved system-level performance. As shown in Figure 6 (a), the system with battery storage more closely followed the building load curve compared to the turbine-only configuration. Daily grid interaction dropped significantly when the battery was included, from over 25 kWh to less than 15 kWh Figure 6 (b). System self-consumption improved from 84.1% to 87.1%, and grid independence rose from 78.0% to 95.5% Figure 6 (c). The rolling system efficiency Figure 6 (e) was consistently higher with the battery—averaging around 82%—compared to about 70% without it. In terms of energy sources Figure 6 (d), 95.2% of the demand was supplied by the turbine, with only 4.8% coming from grid imports. Economic performance Figure 6 (f) was also enhanced with battery integration, shifting the system from a $12 net cost (without battery) to a $2 net gain, due to reduced import costs and improved export potential.

Turbine Efficiency Analysis

Turbine efficiency was further examined across varying flow and head conditions to assess operational consistency and identify performance boundaries. As shown in Figure 7 (a), turbine efficiency increased with flow rate, while generator efficiency remained relatively flat and much lower. Efficiency peaked within the 0.04 to 0.06 cubic meters per second range, consistent with the turbine's design envelope



(a) (b) (c)

(d) (e) (f)

Figure 7 Turbine Efficiency results

Figure 7 (b) demonstrates the relationship between head and efficiency. Turbine performance improved with increasing head, with optimal values observed between 45 and 50 meters. The overall efficiency contour plot Figure 7 (c) clearly highlights this region as the primary zone of high-efficiency operation. Part-load performance 7 (d) indicated that average efficiency improves as the system approaches full load, although it remained below the design benchmark. Over time, as shown in the time-series plot 7 (e), turbine efficiency averaged 20.4%, while generator efficiency remained low, around 18.4% , with both values affected by mismatch and conversion losses. The efficiency distribution histogram Figure 7 (f) confirmed this, with the majority of turbine and generator performance clustered well below the 85% design target. The distribution revealed a narrow standard deviation for turbine performance ($\sigma \approx 4.6\%$), suggesting a predictable but limited range of high-efficiency operation. These findings confirm that the integration of a VRFB with a micro-hydro turbine addresses the challenge of flow variability by enabling time-shifted energy delivery. The combined configuration enhances energy availability, grid independence, and alignment with building demand cycles.

VRFB Efficiency Analysis

The Vanadium Redox Flow Battery (VRFB) was further analyzed to evaluate its charging and discharging efficiency under varying power levels and state-of-charge (SOC) conditions. As shown in Figure 8 (a), both charging and discharging efficiencies remained above 90% across a wide range of power levels, with a slight decline observed beyond 40% of rated capacity. This indicates strong energy conversion stability during partial-load operation.

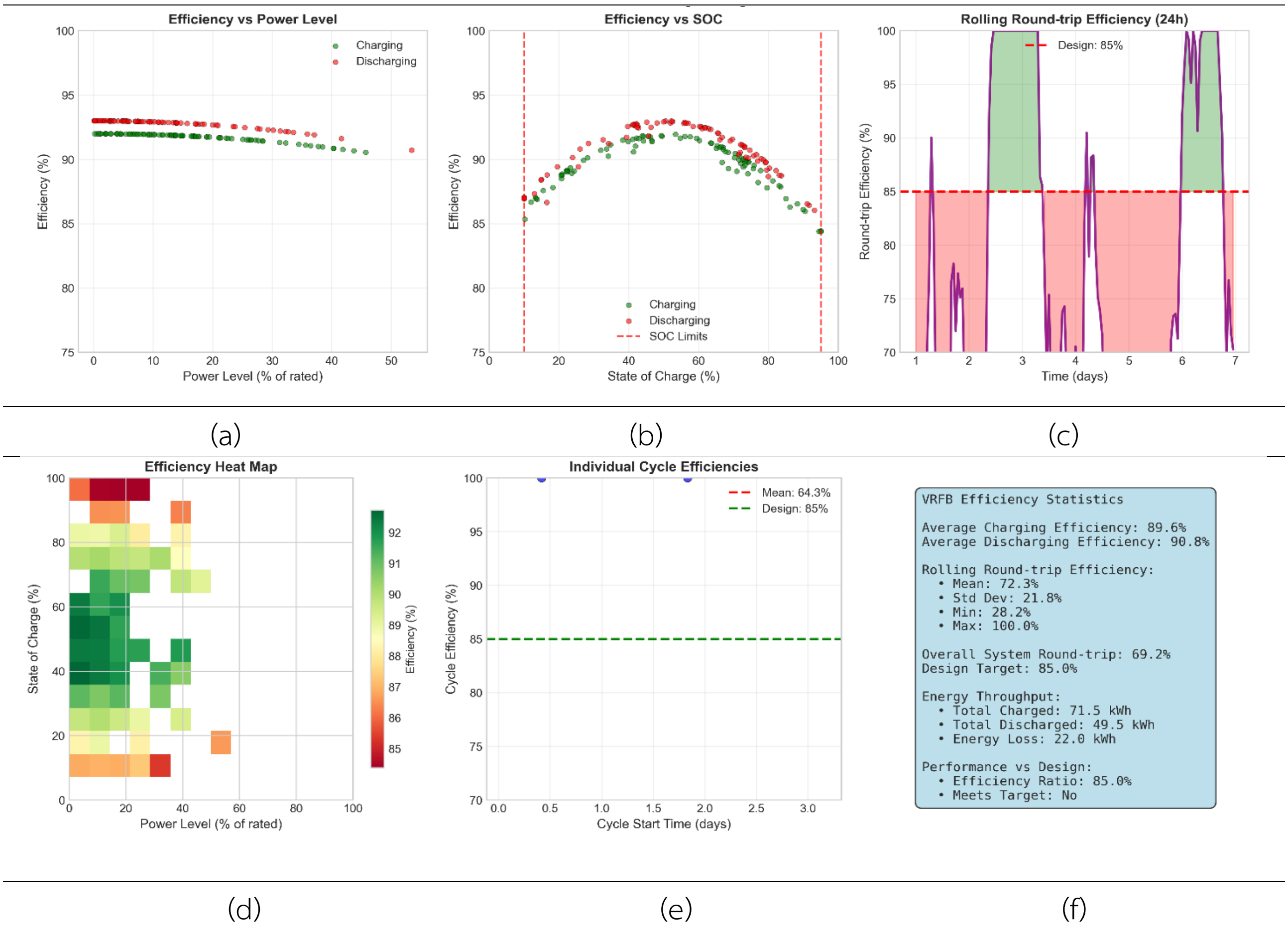


Figure 8 VRFB Efficiency Analysis

Efficiency plotted against SOC Figure 8 (b) reveals a parabolic trend, where both charging and discharging efficiency peaked between 40% and 80% SOC. This aligns with optimal electrochemical stability within the electrolyte system. Efficiency declined near the SOC boundaries (below 30% and above 90%), suggesting increased losses at extreme charge states. The rolling round-trip efficiency Figure 8 (c) fluctuated over the 7-day simulation, with multiple dips below the design benchmark of 85%. The average round-trip efficiency was recorded at 72.3%. The efficiency heat map Figure 8 (d) confirms that the best-performing regions lie within mid-range SOC and lower power levels, reinforcing the importance of controlled operation within this optimal zone. Individual cycle-level analysis 8 (e) shows that no discharge cycles achieved the design target of 85% round-trip efficiency. The mean efficiency per cycle was approximately 64.3%. A summary of the VRFB performance is presented in the statistics box Figure 8 (f). The average charging and discharging efficiencies were 89.6% and 90.8%, respectively. However, the overall system round-trip efficiency reached only 69.2%, with 22.0 kWh of energy loss out of 71.5 kWh charged. These results indicate that although the electrochemical reactions remain efficient, system-level losses likely from auxiliary components such as pumps and control electronics contribute to the observed performance gap.

Discussion

This section interprets the experimental and simulation results, providing technical insights into system behavior, performance trends, and the engineering implications of integrating a Pelton turbine with a Vanadium Redox Flow Battery (VRFB) in a residential wastewater context.

Turbine Operation under Variable Flow Conditions

The Pelton turbine demonstrated strong potential for decentralized energy recovery, particularly within its optimal flow range of 1.2 to 1.5 cubic meters per hour. Power output increased nonlinearly with flow rate, with peak generation reaching 4.77 kW under a head of approximately 50 meters. However, outside the optimal hydraulic envelope, performance declined due to splash losses, turbulence, and nozzle misalignment. These results highlight the importance of real-time flow regulation to maintain turbine operation within its design limits and maximize system efficiency. Despite high hydraulic efficiency from the turbine itself, system-level efficiency was significantly limited by generator performance. The average electrical efficiency of the generator was approximately 20.4%, which contributed to an overall energy conversion efficiency of just 18.4%. This suggests a need for more precisely matched turbine–generator pairs or the integration of power electronics to stabilize output under part-load conditions.

Role and Effectiveness of the VRFB System

The VRFB system played a critical role in smoothing intermittent energy output from the turbine. Simulation results showed stable performance under daily load cycles, with SOC typically maintained between 20% and 90%. While charging and discharging efficiencies were high (averaging 89.6% and 90.8%, respectively), the observed round-trip efficiency at the system level averaged just 72.3%. The efficiency gap is likely attributable to auxiliary power consumption, partial cycling, and suboptimal operation at SOC extremes.

The heatmap and performance statistics revealed that the battery operated most efficiently within 40% to 80% SOC and at moderate power levels. These findings reinforce the importance of intelligent charge–discharge scheduling and SOC management to maintain high round-trip efficiency.

Hybrid System Benefits and Operational Impact

The integration of energy storage into the wastewater energy recovery system significantly enhanced grid independence and operational reliability. Grid import was reduced by over 40%, while the self-consumption ratio and system efficiency increased measurably. Economically, the system transitioned from a $12 net energy cost (without battery) to a $2 net gain with storage, confirming that even small-scale storage can yield positive financial returns when properly integrated. The rolling capacity factor of 58.4% and increased daily power matching with building load profiles suggest that the hybrid system is not only technically feasible but also operationally practical in the context of mid-rise residential buildings in Southeast Asia. However, long-term sustainability will depend on optimizing component sizing, improving conversion efficiency, and incorporating predictive control mechanisms.

Engineering Implications and Deployment Considerations

From an engineering perspective, the study validates the viability of recovering hydraulic energy from building wastewater and storing it effectively using flow batteries. However, system design must carefully account for flow intermittency, generator matching, and battery degradation factors.

To enhance performance, future implementations should consider:

- Installing flow buffers or equalization tanks to maintain steady turbine input.
- Selecting or designing high-efficiency generators tailored to variable-speed turbines.
- Implementing real-time controllers for SOC-based charge scheduling.
- Conducting economic evaluations based on local electricity tariffs and water reuse savings.

Overall, this hybrid approach offers a replicable model for enhancing urban sustainability through combined water and energy resource recovery.

Conclusion

This study presented the design, simulation, and performance evaluation of a hybrid wastewater-to-energy system integrating a horizontal Pelton micro-hydro turbine with a Vanadium Redox Flow Battery (VRFB) for mid-rise residential buildings. The system was developed to address the challenges of low-head, variable-flow wastewater conditions typical in urban environments. Among four turbine designs evaluated, the selected configuration demonstrated optimal performance within the flow range of 1.2 to 1.5 cubic meters per hour, achieving a peak output of 4.77 kW under controlled head conditions. Beyond energy generation, the system enabled the recovery and reuse of up to 60% of treated wastewater for non-potable applications, supporting in-building resource circularity. The VRFB delivered stable charge–discharge performance and mitigated the effects of flow variability, enhancing system resilience and alignment with daily energy demand. Although average round-trip efficiency was 72.3%, the integrated setup improved self-consumption, grid independence, and energy-use consistency. The findings offer field-validated insights into the feasibility of micro-scale energy recovery from building wastewater in tropical urban settings. The proposed configuration provides a replicable model for smart water-energy systems and supports future adoption in resource-constrained developments. Future research should prioritize pilot-scale deployment at actual sites, integration of automated flow control, and predictive VRFB management strategies. Additional opportunities include hybridization with solar PV, battery efficiency enhancement, techno-economic evaluation, real-time monitoring of reuse water quality, and scalability testing across various building types.

Suggestions

1. Integration with Additional Renewable Energy Sources

It is recommended to integrate the wastewater-to-energy system with other renewable energy sources such as solar photovoltaic (PV) systems or bioenergy. This hybrid approach can enhance overall system efficiency, especially during periods with no wastewater flow (no-flow hours).

2. Economic Feasibility Analysis

Future research should expand to include a comprehensive economic evaluation, including Life Cycle Cost (LCC) and Return on Investment (ROI), to support informed decision-making by building owners or stakeholders prior to system implementation.

3. Application in Various Building Types

The system's adaptability should be further studied in different types of buildings, such as office complexes, hotels, or hospitals. Each building type presents unique wastewater flow patterns, which may yield different energy generation outcomes.

4. Design of Wastewater Piping and Flow Control

Vertical piping systems should be designed with adequate height and pressure suitable for micro-turbine installation. Incorporating storage tanks or pressure-regulating valves may help establish a stable pressure head, thereby enhancing power generation potential.

5. Assessment of Solids and Temperature Effects

Real-world testing should take into account additional factors such as the concentration of suspended solids in wastewater and ambient temperature, both of which can impact the efficiency of the Pelton turbine and the VRFB system.

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