Journal of High School Science

A water-first hybrid renewable energy system with gravity-based storage for remote settlements

Ostrovskiy K[1], Sailaukhanuly Y[2]

Submitted: November 19, 2025, Revised: version 1, January 16, 2026, version 2, February 2, 2026, version 3, February 11, 2026
Accepted: February 26, 2026

Abstract
This study proposes a water-first hybrid renewable energy system that integrates solar photovoltaic (PV) and wind generation with gravity-based water storage, treating stored water primarily as household infrastructure while enabling opportunistic electrical energy recovery. During periods of surplus renewable production, excess power drives a DC pump that lifts water from a groundwater source into an elevated storage tank; a three-way diverter valve then directs discharge either for direct household use or through a micro-hydropower turbine to bridge renewable shortfalls. A rule-based controller activates pumping only under renewable surplus and enables turbine-assisted discharge only during renewable deficits when sufficient tank volume is available and battery state of charge is constrained. A time-domain simulation (1 s timestep, 24 h horizon) was evaluated for a representative household case (PV peak 2 kW, mean wind 0.5 kW, electrical load ≈18 kWh/day, water demand 1.2 m³/day) using a 30 m³ tank at 60 m effective head and micro-hydropower generation in the 100–500 W range. In the representative case, hybrid operation recovers 2.83 kWh/day of electrical energy from 5.75 kWh/day of pumping input (recovery fraction ≈49%) and reduces unmet household electrical demand from 5.04 kWh/day to 2.21 kWh/day relative to a direct-use baseline. Daily battery discharge remains modest (~0.36 kWh/day). Monte Carlo analysis over 500 trials with randomized renewable generation, electrical load, and water-use timing (design fixed) demonstrates robust performance, with a mean recovered energy of 2.63 kWh/day (95% CI: 2.60–2.66). These results clarify realistic energy scales for micro-scale gravity storage and position the system as a co-designed water infrastructure with secondary, reliability-oriented electrical energy recovery rather than as a primary electrical storage solution. This work provides one of the first quantitative, stochastic evaluations of household-scale gravity storage co-designed with domestic water infrastructure, establishing realistic upper bounds on recoverable energy and reliability impacts.

Keywords
Hybrid renewable energy systems, Pumped storage hydropower, Energy–water nexus, Off-grid energy systems, Distributed energy storage, Microgrid reliability, Techno-economic analysis, Monte Carlo simulation, Demand-side water–energy integration, Rural electrification

[1]Corresponding author: Kirill Ostrovskiy, Shoqan Walikhanov Private School, Almaty, 050059, Kazakhstan. kirill.19101970@gmail.com
[2]Yerbolat Sailaukhanuly, Shoqan Walikhanov Private School, Almaty, 050059, Kazakhstan.

https://doi.org/10.64336/001c.158347

1. Introduction

Remote households and small settlements frequently experience overlapping challenges related to both energy and water access. Electricity supply is often intermittent due to reliance on diesel generation or variable renewable sources, while water delivery may be limited by infrastructure, terrain, or pumping reliability. Hybrid renewable energy systems combining solar photovoltaic (PV) and wind generation can reduce dependence on fuel logistics, but their inherent intermittency typically necessitates some form of energy storage to ensure reliability. Electrochemical batteries are commonly used for this purpose because of their fast response and ease of integration; however, they remain costly in many regions, degrade with cycling, and require periodic replacement. Pumped-storage hydropower (PSH), by contrast, stores energy in the form of elevated water and has been widely deployed at grid scale for decades. Large-scale PSH installations generally achieve round-trip efficiencies on the order of 70–85%, although performance depends strongly on hydraulic head, flow rate, and equipment sizing (1,2).

At the micro scale, however, the low energy density of gravitational storage becomes a dominant constraint. When head or storage volume is limited, the recoverable electrical energy may be modest, and system performance can be overstated if these constraints are not explicitly accounted for. For this reason, small-scale pumped-storage concepts require careful framing to avoid unrealistic assumptions about energy capacity or efficiency.

1.1 Summary

Given these constraints, small-scale pumped-storage systems are more appropriately interpreted as extensions of water infrastructure that can opportunistically recover energy, rather than as substitutes for electrochemical storage. An elevated tank provides gravity-fed household water supply as its primary function, while electrical energy recovery through a turbine is treated as a secondary capability, used selectively when it offers operational value, such as during periods of renewable generation deficit or during peak demand. The system architecture incorporates a three-way flow diverter that allows stored water to be delivered either directly to the household or routed through a turbine prior to discharge. System operation is governed by a control strategy that activates pumping only during periods of renewable surplus and enables turbine discharge only when renewable generation is insufficient and sufficient tank volume is available. A small electrochemical battery is retained solely to manage short-term transients and control stability.

1.2 Groundwater context for Kazakhstan

Groundwater availability is a key constraint for any water-first energy system. To assess the feasibility of groundwater-based supply in Kazakhstan, national hydrogeological statistics were reviewed. As of the latest state balance, Kazakhstan has over 4,800 registered groundwater deposits with approved exploitable reserves totaling about 43.2 million m^3/day (3). These reserves are allocated across domestic drinking water supply, industrial use, and irrigation, and are defined under a 95% reliability criterion for water-supply systems

(3,4). Explored groundwater reserves are replenished primarily by precipitation and surface runoff and are subject to government regulation, including inventory reassessment and water-use permitting (3,4). This highlights that groundwater is a renewable but finite and regulated resource rather than an unlimited one.

The territorial distribution of drinking-water groundwater in Kazakhstan is uneven. Based on aggregation of regional hydrogeological reserve data compiled under the national hydrogeology program (3), ~ half of exploitable groundwater resources are concentrated in southern regions, about one-third in central, northern, and eastern regions, and less than one-fifth in the western regions (Figure 1). This spatial variation affects the suitability of groundwater-based systems and reinforces the need for region-specific system sizing and regulatory compliance.

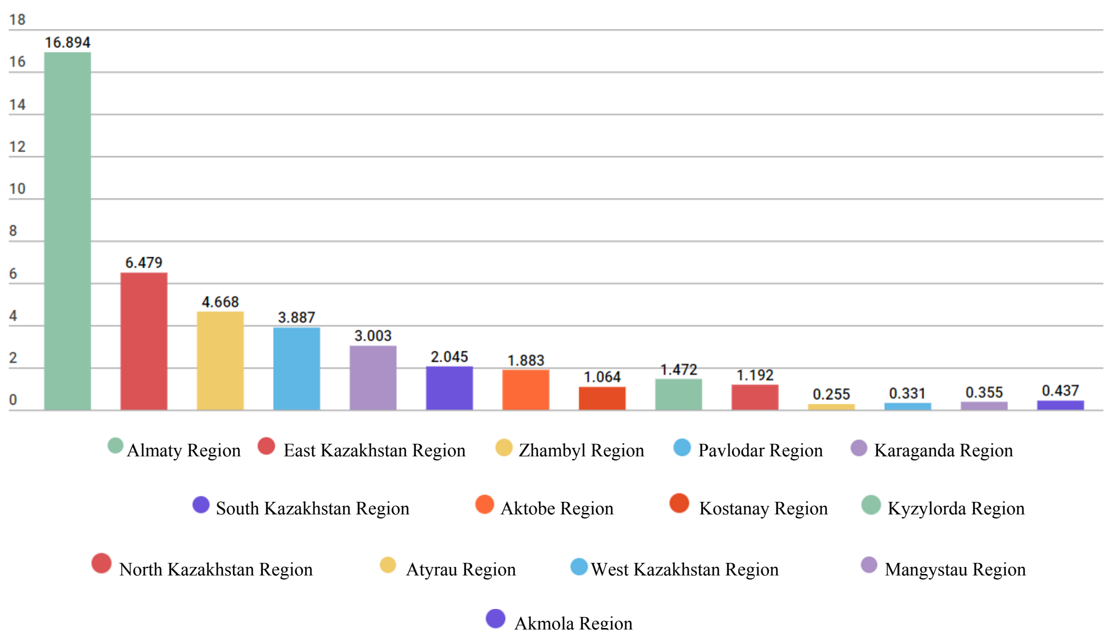

Figure 1. Availability of drinking and technical groundwater resources by region in Kazakhstan (million m³/day).

Importantly, the proposed system is designed to operate within existing domestic water demand and regulatory water-use allocations. It does not require increased net extraction beyond household needs and therefore does not exacerbate aquifer depletion or ecological stress when deployed in accordance with local hydrogeological limits and water-use permits (5,6).

1.3 Related work

The proposed concept is closely related to pumped-storage hydropower (PSH), in which energy is stored by pumping water to an elevated reservoir and recovered by releasing it through a turbine. Reviews of PSH describe its operational roles, storage durations, and typical efficiency ranges across a wide range of installations (1,2). At smaller scales, the micro-hydropower literature provides guidance on turbine selection and system design, including the use of impulse turbines such as Pelton and Turgo units for high-head, low-flow applications (7,8).

A related body of work addresses pumps operating as turbines (PAT), in which conventional centrifugal pumps are operated in reverse as a low-cost alternative to purpose-built turbines for pico- and micro-hydropower. PAT performance prediction, selection methods, and hydraulic–electrical coupling have been examined in detail in prior studies (9,10). Although PATs offer significant cost advantages, their efficiency and operating stability depend strongly on matching the pump, hydraulic head, and electrical load (9,10).

In contrast to conventional PSH systems which are optimized primarily for electrical energy storage, the system studied here is structured around household water demand. Stored water is delivered directly for domestic use, with turbine-assisted discharge enabled only when energy recovery is beneficial. This diverter-based, non-continuous operating mode minimizes unnecessary hydraulic losses and supports a water-first interpretation in which energy recovery is treated as a secondary, opportunistic function of the infrastructure.

2. Methods

2.1 Simulation framework

A time-domain, physics-based numerical model was developed to represent the coupled electrical and hydraulic dynamics of the water-first hybrid energy system under time-varying renewable generation, household electricity demand, and household water use. The simulation was executed with a fixed time step of 1 s over a 24-hour operating horizon, with extended runs used for sensitivity analysis. The time-varying inputs to the model were the renewable electrical power $P_{\mathrm{ren}}(t)$, the household electrical demand $P_{\mathrm{load}}(t)$, and the household water demand $Q_{\mathrm{use}}(t)$. The model tracked the evolution of tank water volume, stored gravitational energy, electrical generation, and battery state of charge under the rule-based control strategy described in Section 2.5.

2.1.1 *Input data and numerical implementation*

The renewable power input $P_{\mathrm{ren}}(t)$ was modeled as the combination of solar photovoltaic and wind generation. Renewable power and household electrical demand were prescribed using the piecewise-constant four-period profile shown in Table 1, representing night, morning, midday, and evening peak conditions. This representation was selected to provide a transparent and reproducible test case for evaluating control behavior.

Household electrical demand $P_{\mathrm{load}}(t)$ was modeled using a representative rural household load profile with morning and evening peaks, a maximum instantaneous demand of 1.2 kW, and a total daily energy consumption of approximately 18 kWh. Household water demand $Q_{\mathrm{use}}(t)$ was fixed at 1.2 m³ per day and distributed over discrete draw events occurring primarily in the morning and evening, consistent with domestic water usage patterns. The coupled hydraulic–electrical system was simulated using an explicit time-domain numerical model implemented in Python. The governing equations for tank volume, pumping power, turbine generation, and battery state were integrated forward in time using an explicit Euler method with a fixed time step of $\Delta t = 1$ s. This time step is sufficiently small to resolve pump, turbine, and control-state transitions without numerical instability. At each time step, the controller evaluated renewable power, household demand, tank level, and battery state of charge to determine the operating mode of the pump, turbine, and battery.

2.2 Component specifications

The system consists of a 30 m³ elevated HDPE water tank at an effective hydraulic head of 60 m. The pumping unit is a variable-speed DC pump with a rated electrical power of 1.5 kW and an efficiency of 70%. Electrical generation is provided by a high-head Pelton micro-turbine rated at 300 W with a turbine efficiency of 80% and generator efficiency of 90%. Water is conveyed through 50 mm PVC piping with lumped losses included in the effective head. A three-way ball valve acts as a diverter, routing water either directly to the household or through the turbine depending on the control state.

2.3 Hydraulic storage model

The elevated tank was modeled using its stored water volume $V(t)$, which evolves according to pumping inflow and household withdrawal. The stored gravitational energy was computed as $E_{\text{tank}}(t) = \rho g H_{\text{eff}} V(t)$, where ρ is the density of water, g is gravitational acceleration, and H_{eff} is the effective hydraulic head, including lumped pipe and valve losses. Tank operation was constrained by minimum and maximum volume limits such that $0 \le V(t) \le V_{max}$.

2.4 Pumping and power generation

When pumping was enabled, the electrical input power required was calculated as $P_{\text{pump}}(t) = \frac{\rho g H_{\text{eff}} Q_{\text{pump}}(t)}{\eta_p}$, where $Q_{\text{pump}}(t)$ is the pump flow rate and η_p is the pump efficiency. When turbine operation was enabled, the recovered electrical power was $P_{\text{gen}}(t) = \rho g H_{\text{eff}} Q_{\text{tur}}(t)\, \eta_t \eta_g$, where $Q_{\text{tur}}(t)$ is the turbine flow rate, $\eta_t$is turbine efficiency, and η_g is generator efficiency. The reference efficiencies used were $\eta_p = 0.70$, $\eta_t = 0.80$, and $\eta_g = 0.90$.

2.5 Control logic implementation

The rule-based hybrid water–energy controller shown in Figure 3 was implemented directly in the simulation. At each time step, the controller evaluated renewable power, household electrical demand, tank volume, and battery state of charge (SOC). The pump was activated only when renewable power exceeded household demand by more than 20% and the tank was not full. The turbine discharge path was enabled only when renewable generation was insufficient to meet household demand $(P_{\text{ren}}(t) < P_{\text{load}}(t))$, the tank volume exceeded an operating threshold V_{thr}, and the battery SOC was below 0.80. Here, $V_{\text{thr}} = 0.20\ V_{max}$ (6 m³ for $V_{max} = 30$ m³). The battery was modeled as a short-term electrical buffer that supplies transient power deficits and stabilizes voltage during switching events, while long-duration energy balancing is handled primarily by the hydraulic storage system. This rule set prevented unnecessary turbine losses during periods of surplus renewable power while preserving stored water for periods of electrical deficit.

2.6 Evaluation scenarios

Two operating scenarios were simulated using identical renewable and demand inputs: [1] Direct-use baseline: stored water is supplied to the household without passing through the turbine, and no electrical energy is recovered. [2] Hybrid recovery mode: water is routed through the turbine according to the control logic, allowing electrical energy recovery during renewable deficits. The difference between these scenarios isolates the contribution of turbine-based electrical recovery.

2.7 Validation and uncertainty treatment

Predicted turbine power, recoverable electrical energy, and round-trip efficiency were benchmarked against reported ranges for micro-hydropower and pumped-storage systems in the literature. Parameter uncertainty was evaluated through sensitivity analysis by varying the effective head and component efficiencies by ±10% to evaluate the sensitivity of recoverable energy and system efficiency.

2.8 Stochastic robustness via Monte Carlo ensembles

The parametric sensitivity analysis (±10% head and component efficiencies) quantifies uncertainty in physical parameters but does not capture day-to-day variability in renewable generation or household behavior. To evaluate robustness under stochastic variability, we therefore performed Monte Carlo simulations over ensembles of PV, wind, electrical load, and water-use timing while keeping the design case fixed.

Across all Monte Carlo trials, the following design and control parameters were held constant: tank volume $V_{\max} = 30$ m³, effective hydraulic head $H_{eff} = 60$ m, nominal pump, turbine, and generator efficiencies, pump and turbine rated powers, battery parameters, and the rule-based control thresholds (pump enabled when renewable power exceeds load by 20%; turbine enabled only when battery state of charge SOC <0.80 and tank volume exceeds $V_{\text{thr}} = 0.20\ V_{max}$ (6 m³ for $V_{max} = 30$ m³)). No design parameters were varied in the Monte Carlo analysis. Each Monte Carlo trial simulated a 24-hour operating period with a 1-second time step using the same coupled hydraulic–electrical model and control logic as the deterministic case. Only the input profiles were randomized within bounded ranges: [1] **PV variability:** the morning PV level (06:00–12:00) and midday PV level (12:00–18:00) were independently perturbed relative to the design profile using multiplicative scaling factors corresponding to $k_{PV,morn} \in [0.8, 1.2]$ and $k_{PV,mid} \in [0.7, 1.3]$, respectively. [2] **Wind variability:** wind power was scaled by a factor $k_{wind} \in [0.7, 1.3]$ (±30%). [3] **Electrical load variability:** household electrical load was scaled by a factor $k_{load} \in [0.8, 1.2]$ (±20%). [4] **Water-use variability:** total daily water withdrawal was held fixed at $1.2\ m^3/day$, while the timing and size of individual draw events were randomized. Discrete draw events were sampled over the day, and event volumes were allocated from a normalized distribution such that the total daily water volume remained constant. For each Monte Carlo run, PV (morning and midday), wind, and electrical load were scaled by independent uniform random factors over the stated bounds. Daily water demand was held fixed at 1.2 m³/day but represented as N_{draw} discrete withdrawal events, where N_{draw} was sampled uniformly from 4–12 events/day. Withdrawal event start times were sampled uniformly over the 24-h day (constrained so each event fits within the day), with a fixed event duration of 3 minutes. Event volumes were generated using a Dirichlet distribution over N_{draw} events and then scaled so that the total daily withdrawal equaled 1.2 m³/day. A total of $N=500$ Monte Carlo trials were performed. For each trial, the following performance metrics were recorded: [1] electrical energy recovered by the turbine E_{gen}(kWh/day), [2] recovery fraction E_{gen}/E_{pump}, [3] battery discharge energy (kWh/day), [4] total turbine operating time (h/day), [5] frequency of low-SOC events (fraction of timesteps with battery SOC < 0.80), and [6] fraction of water bypassing the turbine (ratio of bypassed water volume to total daily withdrawal).

Results are reported as distributions across the Monte Carlo ensemble, including the median, interquartile range, and 5th–95th percentiles. In addition, a 95% confidence interval for the ensemble mean of each metric is reported, computed as $\acute{x} \pm 1.96\ s/\sqrt{N}$, where s is the sample standard deviation across trials. This analysis quantifies the robustness of system performance to realistic stochastic variability in renewable generation and household usage without altering the underlying system design.

2.9 System architecture

Figure 2 illustrates the proposed water-first hybrid renewable system. Solar PV and a wind turbine supply a DC power management stage (including MPPT) that prioritizes household electrical demand. When renewable generation exceeds demand by a margin, power is allocated to a DC pump that lifts water from a source (e.g., well or reservoir) to an elevated storage tank. Household water is delivered by gravity from the tank.

A 3-way diverter at the tank outlet selects between two discharge paths: [1] direct household delivery (normal mode), and [2] a turbine-assisted path (energy-recovery mode) that routes water through a micro-hydro turbine before delivery. The turbine operates non-continuously according to control logic (Section 2.11). A small buffer battery is included only for short transients and control electronics; bulk energy storage is provided by elevated water.

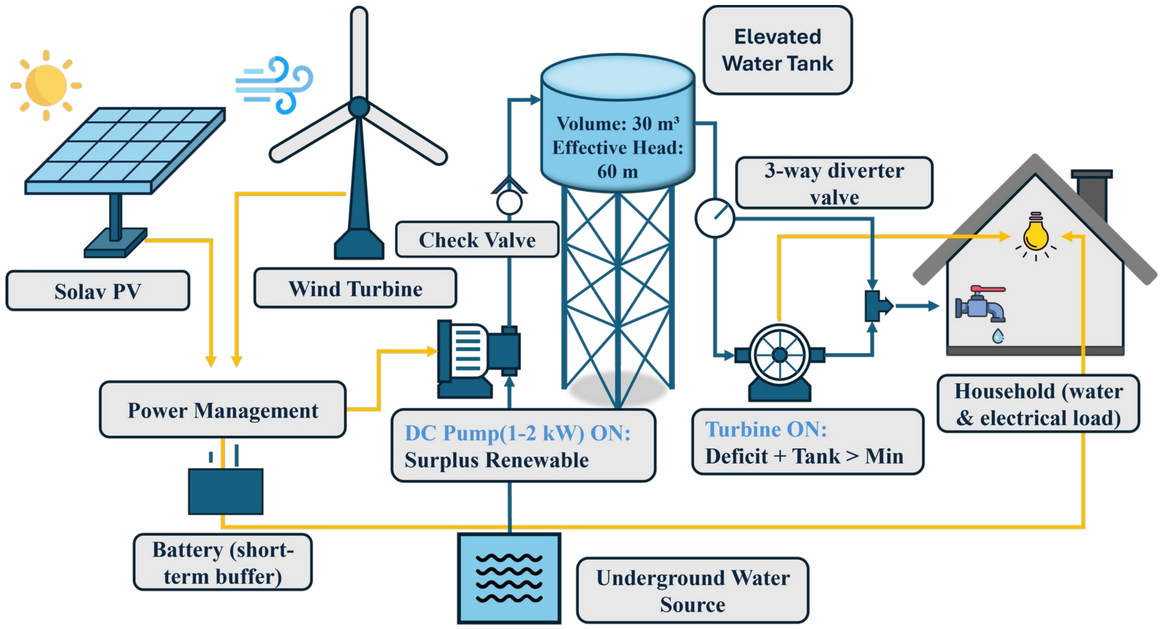

Figure 2. Water-first hybrid renewable system schematic (solar PV + wind → power management → household; surplus → pump → elevated tank; tank discharge via 3-way diverter either direct or through turbine; short-term battery buffer).

2.10 Assumptions and design parameters

The paper evaluates a representative design case with parameters chosen to be realistic for a remote household or small settlement. The following values are used for the energy-balance analysis (Section 4): ρ = 1000 kg/m³, g = 9.81 m/s², tank volume V = 30 m³, effective head H_{eff} = 60 m, pump efficiency ηp = 0.70, turbine efficiency ηt = 0.80, and generator efficiency ηg = 0.90. Effective head accounts for hydraulic losses in piping, fittings, and valves. Daily household water consumption is assumed to be 1.2 m³/day. Component ranges consistent with micro installations include: solar PV (1–3 kW), wind turbine (0.5–2 kW), variable-speed pump (1–2 kW, operated only under surplus), and micro-hydro turbine (100–500 W class, operated only during controlled discharge).

2.11 Operating strategy and control logic

The system uses a hybrid water–energy management strategy that prioritizes household service. The pump charges the elevated tank only when renewable generation exceeds household electrical demand by a margin (e.g., 20%) and the tank is not full. The turbine path is enabled only when renewable generation is insufficient to meet household demand, tank level exceeds $V_{thr} = 0.20\, V_{max}$ (6 m³ for $V_{max} = 30$ m³), and buffer-battery state of charge (SOC) is below a limit (e.g., <80%). The battery is used only to supply transient loads (<15 minutes) and to maintain stable voltage for control and switching.

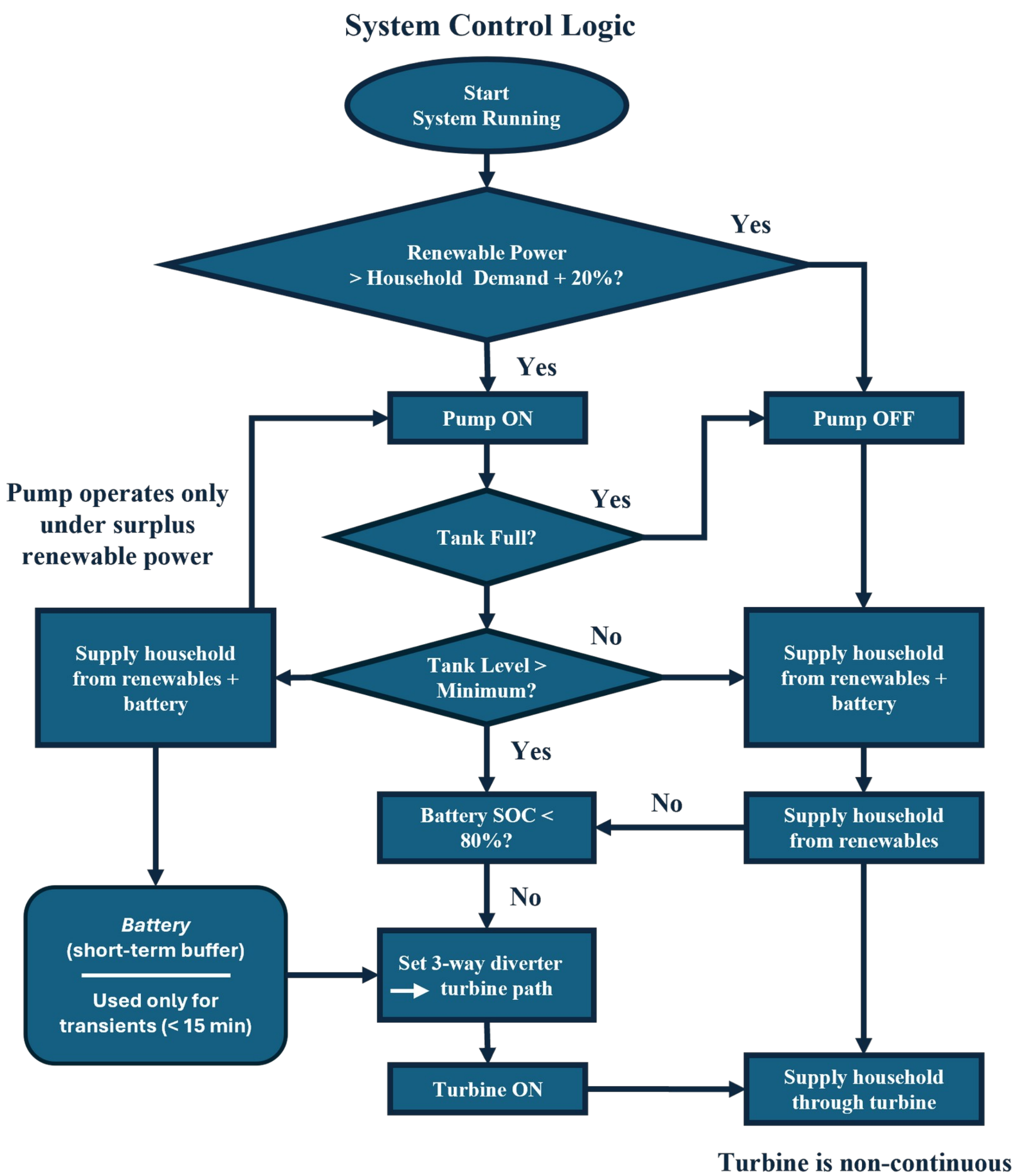

Figure 3. Control logic (pump charging under renewable surplus; diverter selects turbine path under deficit with tank and SOC constraints; battery used only for short transients).

3. Simulation results

3.1 Input profiles

The simulation was evaluated using a representative 24-hour renewable generation and household demand profile typical of a remote off-grid household. The day was divided into four periods representing night, morning, midday, and evening peak conditions. The piecewise-constant electrical input profile used to drive the 1-s time-domain simulation is presented in Table 1.

Table 1. Representative 24-hour renewable generation and household demand profile.

Period (h)	PV Power (kW)	Wind Power (kW)	Total Renewable (kW)	Household Load (kW)
00–06	0.0	0.4	0.4	0.6
06–12	1.2	0.5	1.7	0.5
12–18	2.0	0.6	2.6	0.7
18–24	0.0	0.5	0.5	1.2

Daily household water demand was fixed at 1.2 m^3 and concentrated in discrete morning and evening draw events consistent with domestic usage patterns. For clarity of interpretation, the underlying 1-s numerical simulation was driven by the piecewise-constant renewable and load levels defined in Table 1.

3.2 Baseline vs. hybrid operation

Two operating scenarios were simulated using identical renewable, load, and water-use inputs: [1] **Direct-use baseline** — stored water is always supplied directly to the household and never routed through the turbine. [2] **Hybrid recovery mode** — the turbine is enabled under the rule-based control logic described in Section 2.11. The resulting daily energy flows are summarized in Table 2.

Table 2. Simulated daily energy flows (deterministic 24-h case, buffer-only battery).

Metric	Direct-use baseline	Hybrid recovery mode
Pumping energy input (kWh/day)	3.64	5.75
Electrical energy recovered (kWh/day)	0.00	2.83
Recovery fraction (E_{gen} / E_{pump})	0%	49%
Battery discharge energy (kWh/day)	0.36	0.36
Unmet load energy (kWh/day)	5.04	2.21

In the buffer-only configuration, the electrochemical battery supplies only short transients and does not act as the primary energy storage medium. As a result, daily battery discharge energy remains limited to approximately 0.36 kWh in both the baseline and hybrid cases. The primary benefit of turbine-assisted recovery is therefore not reduced battery cycling, but reduced energy deficit during periods of renewable shortfall. In the representative 24-hour simulation, hybrid operation recovers 2.83 kWh of electrical energy and reduces unmet household electrical demand from 5.04 kWh/day to 2.21 kWh/day. This recovered energy directly offsets renewable deficits that would otherwise require backup generation or load curtailment.

3.3 Tank and turbine behavior

During periods of renewable surplus (06–18 h), the pump charged the elevated tank until full. During evening and night deficits (18–06 h), the control logic enabled the turbine whenever stored water was available and household electrical demand exceeded renewable generation. Since household water use has priority, some tank discharge bypassed the turbine to serve domestic demand, resulting in intermittent turbine operation rather than continuous discharge.

This water-first operating strategy prioritized household water delivery while allowing stored hydraulic energy to be opportunistically converted to electricity during periods of electrical deficit.

3.4 Monte Carlo robustness results

Across 500 Monte Carlo trials with randomized renewable generation, electrical load, and water-use timing—while keeping the system design fixed—the system exhibited consistent performance, with relatively narrow confidence intervals for key energy metrics (Table 3). Electrical energy recovery averaged $E_{gen} = 2.63\ kWh/day$ (95% CI: 2.60–2.66), corresponding to a mean recovery fraction of 0.483 (95% CI: 0.482–0.483), indicating stable conversion performance under stochastic variability. The lower mean recovered energy relative to the deterministic case reflects the inclusion of days with reduced renewable availability and less favorable alignment between water draw events and electrical deficits.

Table 3. Monte Carlo robustness analysis results (N = 500)

Metric	Mean	95% CI (mean)	Median	IQR (p25–p75)	p5–p95
Electrical energy recovered, E_{gen} (kWh/day)	2.6298	[2.6042, 2.6554]	2.7894	[2.4895, 2.8253]	[1.9063, 2.8388]
Recovery fraction, E_{gen}/E_{pump}(–)	0.4826	[0.4819, 0.4833]	0.4821	[0.4784, 0.4871]	[0.4702, 0.4956]
Battery discharge energy (kWh/day)	0.3071	[0.3020, 0.3122]	0.3600	[0.2400, 0.3600]	[0.2400, 0.3600]
Turbine operating time (h/day)	10.7928	[10.6907, 10.8950]	11.0892	[9.6841, 11.8825]	[9.3605, 11.9045]
Low-SOC frequency (fraction of timesteps)	0.5474	[0.5450, 0.5497]	0.5609	[0.5233, 0.5672]	[0.5200, 0.5790]
Water bypass fraction (–)	0.7824	[0.7728, 0.7921]	0.7879	[0.7076, 0.8629]	[0.5805, 0.9490]

The Monte Carlo robustness analysis was performed over 500 trials with fixed system design (30 m³ tank, 60 m head, nominal component efficiencies, fixed control thresholds and component ratings). Morning and midday PV, wind power, electrical load, and water-draw timing were randomized within prescribed bounds while total daily water use was held constant at 1.2 m³/day. Reported statistics include ensemble mean with 95% confidence interval, median, interquartile range (IQR), and 5th–95th percentiles.

Battery discharge energy remained modest (mean 0.31 kWh/day), and the turbine operated for an average of 10.8 h/day. Variability in outcomes is driven primarily by fluctuations in renewable availability and the randomized timing and size of water-draw events. The water bypass fraction exhibited broader dispersion (median 0.79; p5–p95: 0.58–0.95), reflecting that turbine routing was constrained by instantaneous demand and turbine power limits rather than by total daily water availability. Overall, the Monte Carlo results demonstrated robustness of the control strategy and energy-recovery performance to realistic day-to-day variability without altering tank size, head, component efficiencies, control thresholds, or component ratings.

3.5 Model validation

The simulated turbine output (100–500 W class) and recovery fraction (≈45–50%) were consistent with the component-efficiency upper bound and with typical efficiency ranges discussed in micro-hydropower and pump-as-turbine (PAT) literature (8–10), while large-scale pumped-hydro context is provided in (1,2). The recovery fraction was at or below the theoretical upper bound (~50%) implied by the nominal pump, turbine, and generator efficiencies, reflecting bypass flow and the water-first control strategy. This comparison is intended as order-of-magnitude plausibility checking for a conceptual design study. The present work does not constitute field validation; operational performance will depend on site-specific hydraulic losses, equipment matching, controls, and user behavior, which should be evaluated in future prototype testing.

4. Energy-balance and scaling analysis results

The purpose of this analysis is to establish transparent physical bounds on energy storage and recovery using a first-principles energy-balance approach consistent with pumped-storage hydropower. The system is evaluated as water-first infrastructure, in which electrical energy recovery is treated as a secondary function of household water storage rather than as a primary electrical storage device.

4.1 Stored gravitational energy (theoretical capacity)

The gravitational potential energy associated with fully charging the elevated storage tank is $E_{\text{pot}} = \rho g H_{\text{eff}} V$, where ρ is water density, g is gravitational acceleration, H_{eff} is the effective hydraulic head, and V is the stored water volume. Substituting ρ = 1000 kg/m³, g = 9.81 m/s², H_{eff} = 60 m, and V = 30 m³ gives $E_{\text{pot}} = 1000 \cdot 9.81 \cdot 60 \cdot 30 = 1.77 \times 10^{7}$ J, ~ 4.90 kWh. This value represents the maximum theo retical gravitational energy stored when the tank is filled from empty to full.

4.2 Pumping energy required to fully charge the tank

The electrical energy required to store E_{pot} depends on pump efficiency η_p: $E_{\text{pump,full}} = \frac{E_{\text{pot}}}{\eta_p}$. Using a pump efficiency, η_p, value of 0.70 yields $E_{\text{pump,full}} = \frac{4.90}{0.70} = 7.00$ kWh. It is important to distinguish this full-charge energy requirement from the actual daily pumping energy, which is determined by renewable availability and control constraints. In the representative 24-hour simulation (Section

3.2), the pump performs only partial charging, resulting in a daily pumping input of 5.75 kWh rather than a full tank charge.

4.3 Theoretical and realized electrical recovery

The maximum electrical energy recoverable from a fully charged tank during controlled discharge through the turbine and generator is $E_{\text{elec,max}} = E_{\text{pot}}\, \eta_t\, \eta_g$. With η_t = 0.80 and η_g = 0.90, $E_{\text{elec,max}} = 4.90 \cdot 0.80 \cdot 0.90 = 3.53$ kWh.

This represents an *upper bound* corresponding to full-tank discharge with no bypass flow. In practice, the simulated recovered energy is lower (≈2.83 kWh/day in the representative case) because system operation is water-first: household demand has priority, turbine power is limited, and some water necessarily bypasses the turbine during domestic use.

4.4 Round-trip efficiency and interpretation

A theoretical round-trip efficiency for full charge–discharge operation is defined as,

$$\eta_{\text{RTE}} = \frac{E_{\text{elec,max}}}{E_{\text{pump,full}}} = \eta_p\, \eta_t\, \eta_g = 0.70 \cdot 0.80 \cdot 0.90 = 0.504 \approx 50\,\%.$$

At the micro scale, gravity-based storage therefore provides limited but meaningful electrical energy recovery. The recovered electricity—on the order of a few kilowatt-hours for the reference case—is not intended to replace conventional battery storage or provide continuous power. Instead, the system is evaluated as water-first infrastructure, with electrical recovery used selectively during short renewable shortages, evening peak demand periods, or backup operation of critical loads.

5. Discussion

5.1 Cost–benefit and battery-life implications (order-of-magnitude)

This work is conceptual and does not present a site-specific bill of materials; however, order-of-magnitude component costs help clarify the trade-off between added hydraulic hardware and reduced reliance on backup power during renewable shortfalls. For a household-scale implementation, the primary added hardware includes the elevated storage tank (~30 m³), a micro-hydro turbine/generator (or a PAT expander), motorized diverter valves, basic controls and instrumentation, and plumbing/backflow protection. Indicative order-of-magnitude cost ranges are summarized in Table 4.

The benefit of the hybrid approach is reduced reliance on backup power during periods of renewable shortfall, rather than reduced cycling of electrochemical storage. In the representative case (Section 4.3), turbine-based recovery supplies 2.83 kWh/day of electrical energy and reduces unmet household electrical demand from 5.04 kWh/day to 2.21 kWh/day relative to the direct-use baseline. Since the battery is used only as a short-duration buffer (<15 min), daily battery discharge remains limited (~0.36 kWh/day) in both configurations, and system resilience is achieved primarily through hydraulic storage and turbine recovery rather than through deep electrochemical cycling.

Table 4. Order-of-magnitude added hardware cost ranges (indicative).

Hardware	~ Cost
30 m³ storage tank (GRP/HDPE/steel, site-dependent)	\$2,000–\$10,000+
Micro-hydro turbine/generator (~300–500 W class)	\$200–\$1,500+
Motorized 3-way/diverter valve (≈1 in class)	\$50–\$300
Backflow preventer / check valves	\$30–\$250
Sensors + controller (pressure/flow, SOC logic, simple MCU/PLC)	\$50–\$400
Plumbing, fittings, wiring, enclosure (site-dependent)	\$200–\$1,000+

To quantify battery cycling, a simple throughput-based proxy was used: the equivalent full cycles per day are $N_{eq} = E_{dis,day} / C_{bat}$, where $E_{dis,day}$ is the daily battery discharge energy and C_{bat} is the nominal battery capacity (kWh). In the representative deterministic case, $E_{dis,day} \approx 0.36$ kWh/day for both baseline and hybrid operation (Table 2), implying similar N_{eq} for any chosen buffer-battery size. Across the Monte Carlo ensemble, battery discharge remains modest (mean 0.31 kWh/day; Table 3), indicating that the hybrid architecture improves reliability primarily by reducing unmet load rather than by reducing electrochemical cycling. The principal economic benefit is therefore reduced reliance on backup generation during renewable shortfalls, rather than extended lifetime of a large battery bank.

5.1.1 *First-order life-cycle comparison*

To connect the order-of-magnitude hardware costs in Table 4 to practical decision-making, a first-order life-cycle comparison is provided based on two common alternatives for achieving comparable reliability: [1] a battery-only design sized to reduce unmet load to the level achieved by the hybrid system, and [2] a direct-use baseline with only a small buffer battery. In this study's baseline, the battery is intentionally constrained to short-duration buffering (<15 min), so daily battery throughput is already modest; therefore, the hybrid system does not materially reduce cycling relative to this "small-buffer" baseline. Instead, its value is that it reduces unmet load by supplying additional electrical energy via turbine recovery (e.g., 2.83 kWh/day in the representative case and 2.63 kWh/day on average across the Monte Carlo ensemble), thereby potentially avoiding the need for a larger battery bank or more frequent backup generation.

A simple breakeven estimate can be expressed as: $\text{Breakeven years} \approx \dfrac{\Delta C_{\text{capex}}}{\Delta E_{\text{served}} \cdot 365 \cdot c_{\text{backup}}}$ where ΔC_{capex} is the added hydraulic hardware cost as shown in Table 4, $\Delta E_{\text{served}} = E_{\text{unmet,baseline}} - E_{\text{unmet,hybrid}}$ is the reduction in unmet electrical demand attributable to turbine recovery, and c_{backup} is the effective cost of backup electricity (e.g., diesel generator fuel + maintenance). Under this framing, reduced battery replacements become relevant primarily when the counterfactual is a battery-only design that achieves similar reliability by increasing battery capacity and permitting deeper cycling. In such cases, the hybrid architecture can shift storage burden from electrochemical capacity to water infrastructure, allowing a smaller battery bank to remain in shallow cycling and reducing replacement frequency. Because battery lifetime depends strongly on chemistry, depth-of-discharge, and thermal environment, and because backup electricity cost varies widely by site, the breakeven calculation is presented as a parameterized first-order tool rather than a single site-specific claim.

5.1.2 *Economic benchmark vs. battery-only design (order-of-magnitude)*

To provide a quantitative benchmark against a battery-only alternative, we report [1] an illustrative levelized cost of recovered electricity ($/kWh-recovered) for the turbine-enabled configuration and [2] a reliability-per-dollar proxy defined as the reduction in unmet electrical demand per unit annualized cost. We use the Monte Carlo mean recovered electricity (2.63 kWh/day) as the expected recovered-energy throughput and the representative-case unmet-demand reduction (5.04 → 2.21 kWh/day; Δ = 2.83 kWh/day) as the reliability improvement attributable to recovery (Section 4.3). We use the representative-case ΔE_{unmet} from Section 4.2 to maintain direct comparability between the deterministic baseline and hybrid scenarios; Monte Carlo variability primarily affects recovered-energy magnitude and does not materially change the order-of-magnitude reliability improvement.

Since the concept is explicitly water-first, the tank is treated as household water infrastructure; therefore, the primary “energy” incremental cost is the added hydraulic/electrical hardware excluding the tank (turbine, valve, backflow protection, controls, and fittings; Table 4). For annualization we use a standard capital-recovery-factor approach (discount rate 8%): a 15-year life for hydraulic hardware and a 10-year life for Li-ion batteries. For the battery-only benchmark, we assume round-trip efficiency $\eta_{rt} = 0.85$ and usable depth-of-discharge DoD = 0.8 (representative values). An “equivalent” battery capacity that supplies the same deficit energy as the hybrid recovered energy can be estimated as: $C_{eq} \approx \frac{\Delta E_{unmet}}{\eta_{rt} \cdot DoD}$. Using ΔE_{unmet} = 2.83 kWh/day yields $C_{eq} \approx 4.2$ kWh. Thus, the hybrid system’s recovered-energy contribution is comparable, in delivered deficit-energy terms, to adding ~ a 3–5 kWh class battery (depending on DoD and efficiency).

Table 5. Illustrative economic benchmark vs. battery-only storage (order-of-magnitude).

Scenario	Cost
Hybrid (incremental hardware excluding tank; Table 4 items except tank)	CAPEX ≈ \$530–\$3,350 ⇒ annualized cost ≈ \$62–\$391/yr ⇒ \$/kWh-recovered ≈ \$0.06–\$0.41; reliability-per-dollar ≈ 2.6–16.7 kWh of unmet energy avoided per \$ of annualized cost.
Battery-only (3–5 kWh class): usable delivered energy ≈ (3–5)×0.8×0.85 = 2.0–3.4 kWh/day; equivalent capacity to match ΔE_{unmet} is C_{eq} ≈ 4.2 kWh. Using an installed cost range of roughly a few hundred \$/kWh for small Li-ion systems (pack + inverter/BOS), consistent with published residential BESS benchmarks (11).	CAPEX for 3–5 kWh is order-of-magnitude \$900–\$3,000 (and ≈\$1,250–\$2,500 for 4.2 kWh), implying annualized cost ≈\$134–\$447/yr and \$/kWh-delivered ≈ \$0.18–\$0.36 (at ~1 cycle/day).
Sensitivity (if the tank is costed as part of the "energy" system)	adding the tank (\$2,000–\$10,000; Table 4) increases hybrid \$/kWh-recovered to ≈\$0.31–\$1.62, reinforcing that the economic case is strongest when the tank is justified primarily by water-service needs and the turbine loop is treated as an incremental reliability add-on.

Assumptions: discount rate 8%; hydraulic life 15 yr; battery life 10 yr; η_{rt} = 0.85; DoD = 0.8. Recovered electricity uses Monte Carlo mean 2.63 kWh/day (≈960 kWh/yr). Reliability improvement uses representative-case ΔE_{unmet} = 2.83 kWh/day (≈1033 kWh/yr).

5.2 Pump-as-turbine (PAT) alternative to dedicated micro-turbines

Dedicated micro-turbines can be costly or difficult to source for remote deployments. A widely used alternative in pico-/micro-hydropower is pump-as-turbine (PAT) operation, where a standard centrifugal pump is run in reverse to generate electricity. PAT approaches are attractive in low-budget rural systems because pumps are mass-produced, widely available, and easier to service than specialized turbines, though performance is sensitive to matching the available head/flow to the pump's best-efficiency region in reverse mode and to the electrical loading strategy.

For the present concept, a PAT could replace the dedicated turbine/generator if [1] the operating head (~60 m) and available discharge flow during deficit align with a suitable pump's reverse operating point, and [2] a practical generator/load interface is used (e.g., rectification to DC bus or resistive/controlled load). The core conclusions of this paper are unchanged by whether the expander is a dedicated turbine or a PAT: the theoretical upper bound on recoverable energy remains set by ρgHV and component efficiencies, while the realized recovery is reduced by water-first bypass, turbine/PAT power limits, and timing misalignment between deficits and discharge availability.

5.3 Freeze protection and drinking-water quality safeguards

Since the concept is intended for remote households, practical deployment requires safeguards against freezing and water-quality risks. In freezing climates, exposed lines and turbine bypass plumbing can freeze, reducing reliability and potentially damaging equipment. Mitigation options include burying lines below frost depth, insulating above-ground segments, adding automatic drain-down for idle sections, and using freeze-protected routing to prevent trapped stagnant water. These measures may slightly increase cost and can reduce parasitic losses (e.g., heat tracing) compared to battery-only designs, but are standard for cold-climate water systems.

To protect drinking water, the turbine loop should be configured to avoid contamination pathways: include check valves/backflow prevention at interfaces, avoid long stagnation zones, and ensure that any non-potable loop (e.g., groundwater intake, turbine casing materials) is isolated from potable distribution if required by local practice. Any water routed through turbine hardware should use compatible materials and be designed to allow periodic flushing. These safeguards primarily increase system complexity and component count rather than materially affecting the energy-balance conclusions, but they are necessary for real-world implementation.

5.4 Practical and ethical considerations

Groundwater sustainability must be considered in any system that draws from wells or aquifers. The proposed architecture is intended to operate within domestic water needs and does not require additional abstraction beyond household demand. Where groundwater is the source, extraction must comply with hydrogeological limits and local regulations. In Kazakhstan, special water use—including groundwater abstraction—generally requires permitting under the Water Code and related environmental regulation frameworks (5,6).
Practically, users should account for seasonal variability in renewable generation, potential freezing conditions, tank siting constraints, and maintenance requirements for pumps, valves, and filtration. Safety measures should prevent contamination of stored water and ensure secure mounting of elevated tanks.

5.5 Limitations and perspective

This study provides a conservative energy-balance evaluation and a control-oriented architecture. The Monte Carlo simulations provide evidence of the robustness of this particular design to stochastic variability but cannot provide the same evidence for the generalizability of this concept across different designs. Field performance will depend on site-specific hydraulic losses, pump and turbine matching, and operational constraints. Future work should include [1] an instrumented prototype with flow, pressure, and electrical measurements; [2] comparative testing of direct-use vs. turbine discharge modes; [3] optimization of tank sizing versus household water demand; and [4] evaluation of pump-as-turbine options for low-cost deployments.

6. Conclusion

The proposed water-first hybrid renewable system stores surplus renewable energy as elevated water while prioritizing reliable household water supply. A 3-way diverter enables non-continuous turbine operation so that electrical recovery occurs only during renewable shortfalls or peak demand. Energy-balance calculations for a representative design scenario show that micro-scale gravity storage yields limited but meaningful electrical recovery and should be treated as a secondary benefit rather than a stand-alone electrical storage solution. Overall, co-designing water and energy infrastructure can improve resilience and sustainability in off-grid environments.

7. References

1. National Hydropower Association. (2021). *2021 pumped storage report*. https://www.hydro.org/wp-content/uploads/2021/09/2021-Pumped-Storage-Report-NHA.pdf

2. Nikolaou, N. P., Papadopoulos, D. P., Kougias, I., & Theodossiou, N. (2023). A review of pumped hydro storage systems. *Energies,* 16(11), Article 4516. https://doi.org/10.3390/en16114516

3. Scientific and Technical Hydrogeology Program. (n.d.). *Groundwater resources of Kazakhstan*. Ministry of Ecology and Natural Resources of the Republic of Kazakhstan. https://hydrogeology.kz/en/scientific-and-technical-program-megnr-rk/

4. World Bank. (n.d.). *Kazakhstan general water security assessment (General Country Assessment–Kazakhstan) [Report]*. https://documents1.worldbank.org/curated/en/099062424121021579/pdf/P1700301c580430118aca1917d53b41c92.pdf

5. Republic of Kazakhstan. (2003). *Water code of the Republic of Kazakhstan*. Adilet Legal Information System. https://adilet.zan.kz/eng/docs/K2500000178

6. Republic of Kazakhstan. (2021). *Environmental code of the Republic of Kazakhstan*. Adilet Legal Information System. https://adilet.zan.kz/eng/docs/K2100000400

7. Energypedia. (2010). *Hydro scout guide: Micro-hydropower system assessment*. https://energypedia.info/images/3/3b/Hydro_scout_guide_ET_may10.pdf

8. Pacific Power Association. (2020). *Micro hydropower system design guidelines*. https://www.ppa.org.fj/wp-content/uploads/2020/06/Micro-Hydropwer-System-Design-Guideline-V1.pdf

9. Agarwal, T., Singh, P., Jain, S. V. (2016). Review of pump as turbine (PAT) for micro-hydropower. *Renewable and Sustainable Energy Reviews,* 60, 977–990. https://doi.org/10.1016/j.rser.2016.01.122

10. Nasir, A., Frosina, E., Senatore, A., Buono, D. (2024). The pump as a turbine: Performance prediction and review. *Energy Reports,* 10, 120–137. https://doi.org/10.1016/j.egyr.2023.11.012

11. International Renewable Energy Agency. (2017). *Electricity storage and renewables: Costs and markets to 2030*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf