Analysis of a 10 kW mini pumped hydro storage plant with solar integration in Uzbekistan

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Abstract. This paper presents the design and performance evaluation of a 10 kW mini pumped hydro storage (PSH) system integrated with solar photovoltaic (PV) energy for rural electrification in Uzbekistan. The system stores excess solar energy during the day and generates 60 kWh electricity during evening hours at a rated power of 10 kW, with an overall efficiency of about 75 %. The optimized design includes a Cross-Flow turbine (200 mm diameter, 600 rpm), a 10 m head, and 58 solar panels of 400 W. The study demonstrates that such small PSH systems can provide a cost-effective, long-lifetime alternative to chemical batteries in rural power applications.

Keywords: pumped hydro storage, solar photovoltaic system, rural electrification, energy efficiency, cross-flow turbine, renewable energy integration.

1. Introduction

Pumped storage power plants (PSH) are recognized as the most reliable and scalable energy storage technology, with a round-trip efficiency ranging from 70 % to 85 % (IEA, 2020). They play a key role in balancing the variable output of renewable energy sources and in stabilizing power systems. In Uzbekistan, where the average solar radiation is 5-5.5 kWh/m^2 per day, solar generation is one of the fastest growing technologies. However, its variability remains a serious challenge, especially in rural and autonomous areas [1].

Worldwide, pumped storage generation accounts for more than 90 % of installed energy storage capacity, with the largest stations operating in China, the USA, Japan, and Europe [2]. While large PSH plants have traditionally dominated, in recent years there has been increasing interest in small and mini systems (< 100 kW) designed for local needs [3]. Such systems are particularly relevant for Central Asia, where grid expansion is expensive and the terrain is favorable for hydropower development. Mini-PSH provides a sustainable solution for balancing solar generation without the use of costly chemical batteries. Compared to lithium-ion storage, they have a longer lifetime (30-50 years versus 8-12 years for lithium-ion batteries), lower operating costs, and minimal environmental impact, whereas chemical batteries are characterized by high cost, limited capacity, and the need for recycling [4]. Most existing research on pumped storage systems has focused on large-scale plants with capacities above 100 MW, while the potential of mini-PSH (< 100 kW) remains insufficiently studied. In particular, very few studies have been carried out for Central Asia, where solar insolation is high but centralized electricity supply in rural areas is limited. Thus, there is a research gap related to the adaptation of mini-PSH for the conditions of Uzbekistan, which this work seeks to address.

2. Literature review

Small and micro-hydropower plants are actively studied as decentralized solutions for rural electrification. [5] identified their global potential, emphasizing adaptability to remote areas. Later, [6] reviewed new developments in turbines and generators, making mini-hydropower more economical. Cross-Flow turbines have received particular attention due to their simplicity, low cost, and stability under variable discharge conditions [7]. The integration of pumped storage with renewable energy sources has been implemented in a number of hybrid systems. [8] showed that solar-PSH hybrids can smooth fluctuations in solar panel output. Similar conclusions were made by [9] for "wind-PSH" systems in Korea. For arid and semi-arid regions, solar-hydro hybrids are particularly advantageous because of high solar insolation [10].

Research on small PSH plants has begun to grow actively in recent years. [11] demonstrated the feasibility of micro-PSH systems for autonomous Turkish villages, showing that capacities of 5-20 kW are sufficient for stable electricity supply. Similar studies in India [12] confirmed the economic viability of small PSH in combination with solar power plants. Nevertheless, challenges remain: the need for land for reservoirs, high capital thresholds, and efficiency losses at small scales [3]. However, modular design and new materials are gradually reducing costs. Thus, there is a clear research gap in the application of mini-PSH in Central Asia, which defines the relevance of this article. The use of intelligent sensors to measure and control the rotational angular displacement of micro-engines increases their performance. Such intelligent sensors have been used in agricultural machinery [13-15]. Today, such hybrid energy systems are being used in various regions of Uzbekistan [16]. In addition, mini and micro hydropower plants do not affect the structural composition of water [17]. It is even possible to power some actuators with solar panels [18].

3. Materials and methods

The study applies mathematical models of hydropower processes that describe the conversion of the potential energy of water into electrical power, as well as determine the parameters of the pump-turbine cycle. The methodology includes:

– Energy model: the power equation $P = \eta \cdot \rho \cdot g \cdot Q \cdot H$, describing the dependence of output power on head and discharge.

– Cycle energy balance: calculation of input and output energy taking into account efficiency, which makes it possible to determine the effectiveness of pumped hydro storage.

– Hydraulic models: equations for calculating flow velocities, pipe diameters, and hydraulic losses during pumping and generation.

– Reservoir geometry model: determination of the relationship between surface area and depth for a fixed storage volume.

– Parametric optimization method: selection of optimal Cross-Flow turbine parameters (speed ratio, rotational frequency, runner diameter) to match the generator and ensure maximum efficiency. Based on these models, calculations were carried out for the parameters of generation, reservoir, pumps, turbine, and solar integration, which are presented below.

Initial parameters: Evening generation time: $t_g = 6$ h. Daytime pumping time: $t_p = 5$ h. Power: $P = 10$ kWh. Head: $H = 10$ m.

Water pumping and solar integration discharge during generation: $Q_g = \frac{P}{\eta \rho g H} = \frac{10 \cdot 10^3}{0.75 \cdot 1000 \cdot 9.81 \cdot 10} = 0.136$ m^3/s, where η – efficiency (assumed 0.75), ρ – water density (1000 kg/m^3), g – gravitational acceleration (9.81 m/s^2), Q – discharge (m^3/s), H – head (m).

Active water volume to be discharged during generation: $V = Qt_g = 0.136 \cdot 6 \cdot 3600 = 2937.6$ m^3. Pumping discharge: $Q_p = \frac{V}{t_3 \cdot 3600} = \frac{2937.6}{5 \cdot 3600} = 0.163$ m^3/s (585 m^3/h). Water energy will be: $E = mgH = \rho V g H = 1000 \cdot 2937.6 \cdot 9.81 \cdot 10 = 288178560$ J ≈ 80.05 kWh. Taking into account cycle efficiency (~75 %) the required energy is: $E_{pump} = \frac{E}{0.75} = \frac{80.05}{0.75}$ = 106.73 kWh.

With average solar insolation of 5 h/day, the required solar power considering a 10 % reserve (dust, temperature, tilt angle) is: $P_{pv} = 1.1 \cdot \frac{E_{nas}}{t_3} = 1.1 \cdot \frac{106.73}{5}$ = 23.48 kW.

Taking into account losses, starting torque, and possible efficiency reduction, a pump with a reserve of 25 kW is selected.

Solar panels used: P_1 = 400 Wh, in quantity: $N_{pv} = \frac{P_{pv}}{P_1} = \frac{23.48 \cdot 10^3}{400}$ = 58. Total area of panels: $S_{pv} = N_{pv} \cdot S_1 = 58 \cdot 2 = 116$ m^2, where the area of one panel $S_1 \approx 2$ m^2.

Table 1. Final calculated parameters of the 10 kWh mini-PSH with solar panel integration.

Parameters	Names	Magnitude
Generation power	P	10 kW
Head	H	10 m
Water discharge during generation	Q_g	0.136 m^3/s
Pumping discharge	Q_p	0.163 m^3/s
Active water volume	V	2937.6 m^3
Water energy	E	80.05 kWh
Energy considering efficiency	E_{pump}	106.73 kWh
Solar panel power with reserve	P_{pv}	23.48 kW
Number of panels	N_{pv}	58 units
Total area of panels	S_{pv}	116 m^2

Hydraulic Elements. Jet velocity during generation (discharge): $v_g = C_V\sqrt{2gH} = 0.98\sqrt{2 \cdot 9.81 \cdot 10} = 13.73$ m/s, where $C_V = 0.98$ is the nozzle velocity coefficient for a cross-flow turbine.

Pipe diameter calculation formula: $Q = A \cdot v = \left(\frac{\pi d^2}{4}\right) \cdot v$.

Generation pipe. Diameter: $d_g = \sqrt{\frac{4Q_g}{\pi v}} = \sqrt{\frac{4 \cdot 0.136}{3.14 \cdot 13.73}}$ = 0.112 m = 11.2 sm.

Cross-sectional area: $A_{pipep} = \frac{\pi d^2}{4} = \frac{3.14 \cdot 11.2^2}{4}$ = 98.47 sm^2.

Pumping pipe. Diameter: $d_p = \sqrt{\frac{4Q_p}{\pi v}} = \sqrt{\frac{4 \cdot 0.163}{3.14 \cdot 2}}$ = 0.322 m = 32.2 sm.

Water lifting velocity: v_p = 2 m/s.

Cross-sectional area: $A_{pipep} = \frac{\pi d^2}{4} = \frac{3.14 \cdot 32.2^2}{4}$ = 813.91 sm^2.

When sizing the pumping pipe, an optimal flow velocity of 2 m/s is considered. Higher velocities reduce the pipe diameter and material cost, but significantly increase hydraulic losses, energy demand, and risks such as erosion, noise, water hammer, and cavitation. Total reservoir volume. The total reservoir volume, including a 10 % dead storage allowance (to account for factors such as sedimentation, suction vortex, and safety margin), is: $V_{tot} = V \cdot 1.1$ = 2937.6·1.1 = 3231.36 m^3.

The water surface area is calculated as $A_{surf} = \frac{V_{tot}}{h}$, and the reservoir area with side slopes is estimated as $S \approx 1.3 \cdot A_{surf}$.

Based on the total volume V_{tot} = 3231.36 m^3, the reservoir dimensions for different depths h are calculated and summarized in the Table 2.

Turbine selection. The type of turbine is chosen based on the following parameters shown in Table 3.

Based on the table, a Cross-Flow turbine is selected, as it is suitable for small/medium flows and low/medium heads. For $H = 10$ m, $Q = 0.136$ m^3/s, the Cross-Flow turbine provides a simple, cost-effective design with an efficiency of $\eta \approx 0.75$, and performs well under variable flow rates

Q and water contamination.

Optimal speed ratio for Cross-Flow turbines: $\phi = \frac{u}{v} = 0.4 - 0.5$.

Peripheral (tangential) velocity of the runner: $u = \phi v_g = 0.45 \cdot 13.73 = 6.1785$ m/s.

Relation between peripheral velocity, diameter, and rotational speed: $u = \frac{\pi \cdot D \cdot n}{60}$, where n is the rotational speed in revolutions per minute (rpm). Runner diameter: $D = \frac{60 \cdot u}{\pi \cdot n} = \frac{60 \cdot \phi v}{\pi \cdot n}$.

The turbine parameters are selected based on the following results shown in Table 4.

Table 2. Reservoir parameters for different depths h

Parameters	Symbol	Depth 2 m	Depth 3 m	Depth 4 m	Depth 5 m
Water surface area	A_{surf}	1615.68 m^2	1077.12 m^2	807.84 m^2	646.27 m^2
Reservoir area with slopes	S	2100.38 m^2	1400.26 m^2	1050.19 m^2	840.15 m^2
Reservoir dimensions (square, 1:1)	–	45.8×45.8 m	37.4×37.4 m	32.4×32.4 m	29.0×29.0 m
Reservoir dimensions (rectangle, 1.5:1)	–	56.1×37.4 m	45.9×30.6 m	39.8×26.5 m	35.5×23.7 m

Table 3. Parameters of hydraulic turbines

Head (H)	Flow rate (Q)	Turbine type
High: $H \approx$ 150-200 m	Low: $Q \approx$ 0.005-0.01 m^3/s	Pelton
Wide range: $H \approx$ 10-300 m	Medium and high: $Q \approx$ 0.1 up to hundreds of m^3/s	Francis
Low: $H \approx$ 2-30 m	High: $Q \approx$ tens to hundreds of m^3/s	Kaplan or propeller
Low and medium: $H \approx$ 5-50 m	Low: $Q \approx$ 0.005-0.01 m^3/s	Cross-Flow

Table 4. Runner diameter D at rotational speeds of 500, 600, and 750 rpm, and speed ratios $\varphi = 0.4$ and $\varphi = 0.45$

$\varphi \left(\frac{u}{v}\right)$	n, rpm	U (peripheral velocity, m/s)	D, mm	Nozzle height $a \approx \frac{D}{10}$, mm	Nozzle width b, mm
0.40	500	5.49	210	21.0	472
0.40	600	5.49	175	17.5	567
0.40	750	5.49	140	14.0	708
0.45	500	6.18	237	23.7	419
0.45	600	6.18	198	19.8	502

According to the table, the most optimal option is: $\phi = 0.45$, $D \approx 200$ mm, $n = 600$ rpm.

This combination provides:

– Good hydraulic performance.

– A convenient runner size.

Nozzle (slot) position relative to the turbine runner:

Jet angle – angle of attack relative to the tangent: 16 (recommended value). The jet entry point is located at the outer part of the runner. The distance from the nozzle edge to the runner contact point is about 1-2 jet thicknesses, which in this design corresponds to 19.8-39.6 mm. To ensure uniform filling of the inlet channels of the runner blades, the nozzle shape is designed along an arc.

Generator selection: For a mains frequency of 50 Hz and a turbine runner speed of 600 rpm, we use a generator with synchronous speed in the range 500-750 rpm. Based on the Table 5, a generator operating at 600 rpm corresponds to 10 poles.

4. Results and discussion

The designed mini-pumped storage power plant (mini-PSPP) provides evening electricity generation of 60 kWh with an installed capacity of 10 kWh over a period of 6 hours. To accumulate the required amount of energy, daytime pumping of approximately 107 kWh is needed, which corresponds to an overall cycle efficiency of about 75 %. Thus, the plant effectively compensates for the intermittency of renewable generation and ensures reliable coverage of the evening peak demand through hydro storage.

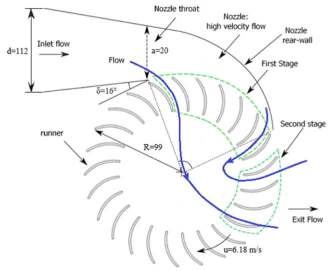

Fig. 1. Nozzle and Cross-Flow turbine runner

Table 5. Correspondence between generator poles and rotational speed (50 Hz)

Poles	Synchronous speed (rpm)
2	3000
4	1500
6	1000
8	750
10	600
12	500
14	428.6
16	375

Table 6. Generator parameters

Parameter	Value
Generator type	Synchronous with AVR (automatic voltage regulator – stable frequency/voltage)
Power	12-15 kW
Poles	10 (for 600 rpm selection)
Gearbox	Low-loss gearbox with protection against hydraulic water hammer

The analysis of the relationship between reservoir water surface area and depth shows that increasing the depth from 2 m to 5 m reduces the surface area from 1615.68 m^2 to 646.27 m^2. This indicates that increasing the reservoir depth significantly reduces the required land area while maintaining the same storage volume. Therefore, selecting a greater reservoir depth is a more spatially efficient solution in the design of a pumped storage system.

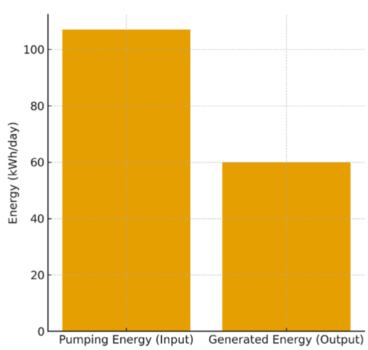

Fig. 2. Energy balance of the 10 kW mini-PSPP

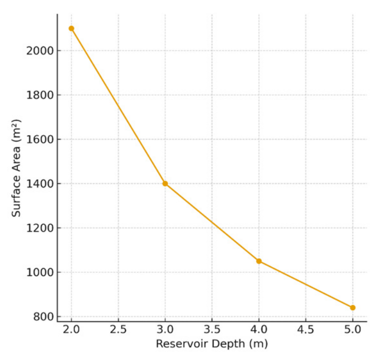

Fig. 3. Dependence of water surface area on reservoir depth

The calculation results show that increasing the rotor speed from 500 to 750 rpm at a fixed speed ratio φ leads to a reduction in the runner diameter (from 210 to 140 mm at $\varphi = 0.40$; from 237 to 159 mm at $\varphi = 0.45$). At the same time, the nozzle height decreases proportionally, while its width increases (from 472 to 708 mm at $\varphi = 0.40$; from 419 to 624 mm at $\varphi = 0.45$). This indicates that higher rotational speed allows the use of a more compact runner, but requires an elongated nozzle slot, which must be taken into account in turbine design.

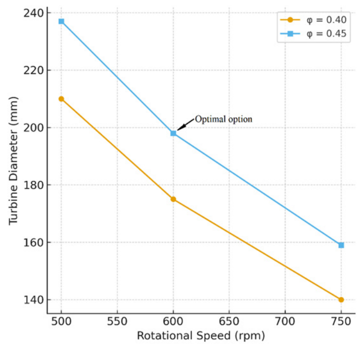

Fig. 4. Dependence of turbine diameter on rotational speed at $\varphi = 0.40$ and $\varphi = 0.45$

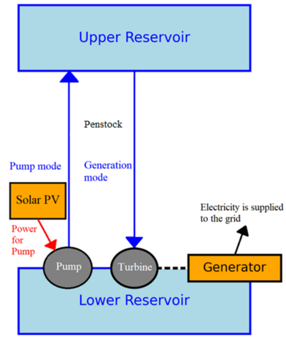

Fig. 5. Schematic diagram of a 10 kW mini-PSPP with solar integration

Technical Advantages: stable daily operation, integration with solar panels smooths generation fluctuations, more cost-effective and durable compared to lithium-ion batteries, minimal carbon footprint.

Limitations: requires suitable topography for reservoirs, high capital investment, efficiency is sensitive to pipeline losses.

Sensitivity Analysis: a parametric sensitivity analysis was carried out with respect to head H and flow rate Q. For variations of ±10 % and ±20 % from the design values, proportional changes in output power were observed (see Table 7). In particular, a simultaneous reduction of H and Q by 10 % results in a power decrease of ≈19 %, highlighting the need for design margin in reservoir volume or backup pump capacity to ensure the rated output of 10 kW.

Table 7. Proportional changes in output power were observed

ΔH	ΔQ	P (kW)	ΔP (%)
−20 %	−20 %	6.404	−36.0 %
−10 %	−10 %	8.105	−19.0 %
0 %	0 %	10.006	0.0 %
+10 %	+10 %	12.108	+21.0 %
+20 %	+20 %	14.409	+44.0 %

Comparison with previous studies (Table 8): the results of this work are compared with the studies of [11], [12] and [2]. All of these studies examine mini-PSH systems of similar scale (5-20 kW) and also highlight the advantages of pumped hydro storage over chemical batteries in terms of lifetime and maintenance cost. Unlike several works that rely on higher heads and larger reservoir surface areas, the proposed configuration (H = 10 m, active volume = 3231.36 m^3) achieves a comparable round-trip efficiency (~75 %) with a smaller land footprint due to the increased reservoir depth.

5. Conclusions

This study has developed and analyzed a 10 kWh mini pumped storage hydropower (mini-PSH) system integrated with solar photovoltaic generation for rural electrification in Uzbekistan. The obtained results confirm the technical feasibility of using small-scale PSH plants to store surplus solar energy during the day and supply stable electricity during evening peak hours. The designed system provides an average daily output of 60 kWh at a rated power of 10 kWh, achieving an overall round-trip efficiency of approximately 75 %.

Table 8. Comparative summary of mini-PSH studies (Turkey, India, China, Uzbekistan)

Parameter	Ozturk et al. (Turkey, 2020)	Kumar & Singh (India, 2021)	Zhang et al. (China, 2021)	This work (Uzbekistan)
System type	Micro-PSH with solar integration	Small PSH with solar PV	Large-scale PSH, < 100 kW noted as promising	Mini-PSH with solar integration
Power rating	5-20 kW	< 20 kW	Hundreds of MW-GW (small-scale considered promising)	10 kW
Key findings	Technically feasible and economically viable for rural areas	Alternative to batteries, suitable for decentralized supply	Large plants dominate, but small units are important for distributed energy	Feasible for rural electrification, 60 kWh/day, efficiency ≈ 75 %
Limitations/ conditions	Requires suitable topography, reservoir costs	Dependent on hydrological conditions	Limited research on small-scale systems	Requires favorable terrain and investment in pumps and reservoirs
Parameter	Ozturk et al. (Turkey, 2020)	Kumar & Singh (India, 2021)	Zhang et al. (China, 2021)	This work (Uzbekistan)

The optimization of turbine dimensions and reservoir parameters demonstrates that such configurations can be effectively adapted to local geographic and climatic conditions. The proposed system represents a practical alternative to chemical energy storage, offering improved sustainability and reliability for decentralized power supply in rural regions. However, the research is limited to computational modeling and does not include experimental validation. Future studies should focus on prototype testing under real operating conditions, detailed evaluation of hydraulic losses, and comprehensive techno-economic assessment, including equipment costs and life-cycle efficiency. Overall, the presented concept contributes to the advancement of hybrid renewable energy solutions suitable for Central Asian rural areas.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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