Assessment of small hydroelectric power plants in the Syunik region of the republic of Armenia

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Abstract. The focus of this study is the performance of small hydroelectric power plants (SHPPs) in Armenia's Syunik region, especially the Tatev SHPP along the Vorotan River. This study is undertaken from a multifaceted approach involving hydropower simulation models and environmental assessment using the Leopold matrix. Most impacts are ecological, and protecting the river flow and aquatic habitats is essential, especially considering the predicted decrease in water discharge due to climate change by 15-30%. However, the good news is that these small hydro projects result in a carbon footprint reduction of about 3,500 tons of CO_2 emissions and create employment opportunities for the surrounding communities. The entire data collection has brought out that the small-sized hydroelectric projects for which the planning and management were carried out in detail are instrumental/will be instrumental in the transition of the Armenian energy system to cleaner and more absolutely sustainable energy.

1 Introduction

Armenia is vulnerable to threats to its energy security and economic stability because its energy sector is still largely dependent on imported fossil fuels — mostly natural gas and massive hydropower cascades. Meeting growing energy demands while shifting toward sustainable and environmentally responsible power generation continues to be a major challenge [1]. Small hydroelectric power plant (SHPP) development is also strongly encouraged by socioeconomic pressures environmental concerns and Armenias pledges to renewable energy under the Paris Agreement. The mountainous terrain and river system of the Syunik region in southern Armenia which includes the 194-kilometer-long Vorotan River with a 5540-kilometer catchment area make it an especially good place to deploy SHPP [2]. Due to its considerable elevation variation—from 3045 meters at its source to its confluence with the Araks River—and combination of precipitation groundwater and snowmelt the Vorotan River is ideally suited for small-scale hydropower production. According to prior research Armenia offers a strategic opportunity for energy

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diversification with more than 400 possible SHPP locations with a combined capacity of more than 500 MW [3]. A number of locations in Syunik have been found to have the potential to produce about 550000 kWh annually which would save about 121 tons of organic fuel annually [2]. Notwithstanding this promise there are currently few comprehensive evaluations that consider climate change adaptation environmental sustainability and economic viability in the Armenian context. In addition to discussing the wider regional potential this study attempts to present a comprehensive case study of the Tatev SHPP and a combined economic and ecological assessment of SHPPs in the Syunik region. The particular goals are as follows. Evaluate SHPPs economic feasibility by conducting a thorough financial analysis of various site kinds. Analyze the effects on the environment considering variations in river flow and biodiversity. Analyze the climate change vulnerabilities. Provide suggestions for sustainable development that strike a balance between ecosystem preservation cost-effectiveness and energy production.

2 Literature review

Kumar et al. developed maintenance cost correlations for high-head run-of-river SHPPs, demonstrating that capacity and hydraulic head are major cost determinants, with operation and maintenance (O&M) costs typically ranging from 2-4% of CAPEX annually. Investment cost analyses in the Euphrates and Tigris basins show how flow rate, head, and hydrological uncertainties directly affect amortization periods and levelized cost of energy (LCOE), with payback periods of 7-15 years common for well-sited projects [4]. Environmental impacts of small hydropower differ substantially from large-scale projects but remain significant. Kibler and Tullos found that while SHPPs have lower environmental impacts than large dams, they still affect river ecology through flow regime alterations and habitat fragmentation [5]. Climate change considerations have become increasingly prominent. Schaefli et al. demonstrated that hydropower generation in mountainous regions is vulnerable to changing precipitation patterns and reduced snowpack [6]. Skoulikaris et al. found that reductions in river discharge of 15-30% may reduce generation by similar proportions, with particular vulnerability during dry seasons when environmental flows are most critical. Regional reports indicate that climate change is already reducing water availability in Armenia, threatening both economic and ecological sustainability of hydropower projects [7]. Armenian-specific research reveals important contextual factors. Papikyan and Papikyan (2024) mapped mini-HPP possibilities in Syunik and calculated preliminary energy yields, demonstrating technical feasibility at multiple sites including installations at approximately 1,810 m elevation on the Vorotan system. However, local reports indicate that Armenia's SHPP sector sometimes operates without full compliance with environmental flow requirements, with some facilities extracting more water than permitted, harming spawning fish and aquatic biodiversity [2, 8-10].

3 Materials and Methods

3.1 Research Area and Site Selection

The research focuses on SHPP locations in Armenia's Syunik region, with the Tatev SHPP located on the Vorotan River being the specific location. The Vorotan River is the biggest tributary of the Araks River, 129 km in length within Armenian borders with area of catchment 2,020 km² and mean elevation 2,280 m. Locations were chosen at 1,810-3,045 m altitudes by Papikyan and Papikyan (2024) [2].

3.2 Technical Specifications

Tatev SHPP parameters: design capacity 1,400 kW, design flow 3.5 m³/s, static head 59.0 m, annual generation 6.67 million kWh, and saleable electricity 6.40 million kWh (in view of losses of 4%). Regional small sites generate annually about 550,000 kWh with fuel saving of ~121 tons/year [2]. All the installations are run-of-river based on design with environmental flow provisions.

3.3 Economic Assessment

For 25 to 30 years of operation, the conventional methods of hydropower evaluation were used to conduct a financial analysis [4]. The capital investments included the powerhouse, pressure pipeline, intake structures, electromechanical equipment (turbine and generator), and transmission facilities. It was assumed that the business would cost 2–4% of initial capital cost per year to operate and maintain. The revenue forecasts were calculated with reference to Armenia's regulated power price of 23.805 AMD/kWh ($0.05/kWh). We evaluated the project economic feasibility with reference to different economic criteria: Internal Rate of Return (IRR), Net Present Value (NPV at 5%, 8%, 10%, and 12% discount rates), payback time, as well as Levelized Cost of Energy (LCOE). The economic analysis considered Armenia's tax environment, including 20% corporate profit tax, property tax of 0.6%, as well as 20% value-added tax [8].

3.4 Environmental Impact Assessment

Environmental evaluation entailed integrating screening checklists and Leopold matrix, evaluating physical, biological, and social environment effects [5]. Electronic environmental flow needs guaranteed international best practice. Climate risk was estimated through regional projections indicating possible 15-30% flow reductions in dry phases [7]. Measures to mitigate included dust suppression from development activities, promotion of riparian vegetation, waste management, and environmental flow regulation.

3.5 Data Sources

Data was gathered from: Papikyan and Papikyan (2024) for site-specific parameters; Armenian Hydrometeorological Service; national SHPP reports; 2024 price of materials; Armenian energy legislation; and foreign literature to determine the cost relationships and the environmental models.

4 Results and Analysis

4.1 Economic Analysis - Regional Sites

Economic analysis demonstrates project viability (IRR 11.73%, payback 8.2 years) (Authors' calculations based on data from [2]), but environmental considerations present more complex challenges requiring detailed examination

Table 1. Economic Metrics for Representative Syunik Sites

Metric		Value	Source
Annual energy generation		~550,000 kWh	Papikyan & Papikyan, 2024
Fuel saving (organic fuel)		~121 tons/year	Papikyan & Papikyan, 2024
Payback period		7-12 years	Estimated from discount rates 5-12%
LCOE range		5-8 AMD/kWh	Derived from investment costs
O&M as % of CAPEX		2-4%/year	Kumar et al., 2020

Sensitivity analysis across multiple sites shows: payback periods of 7 years under favorable conditions (high head, reliable flows, 5% discount rate) extending to 12 years under more conservative assumptions (8-12% discount rates, moderate hydrological variability). These ranges align with international comparisons from Euphrates/Tigris basin studies showing similar payback periods when flows are reliable.

Sensitivity to Hydrological Variability: Using projections from Skoulikaris, reductions in river discharge of 15-30% due to climate change may reduce generation by similar proportions. For the 550,000-kWh site, a 20% flow reduction would decrease annual output to 440,000 kWh, extending payback periods by approximately 2-3 years and reducing fuel savings to ~97 tons annually.

4.2 Environmental Impact Assessment Results

Screening Results: Eleven potential impact areas identified requiring attention for Tatev SHPP. Definite impacts: land excavation (>1.0 hectare), proximity to water bodies, water abstraction/discharge. Possible impacts: wastewater effects, construction disturbances, fuel storage, noise increases. Beneficial impact: significant air quality improvement displacing thermal generation [5].

Leopold Matrix Analysis:

Physical Environment:

- Construction: Moderate negative soil impacts (1.2 hectares, temporary, reversible); minor groundwater impacts; minor air quality impacts from dust; moderate noise (5-10 decibel increase, temporary)
- Operation: **Significant positive air quality impact** – 3,500 tons CO_2 avoided annually plus NOx pollutants; minor water quality impacts in 0.85 km derivation section [6]

Biological Environment - Critical Findings:

- **Seasonal flow deficits:** In dry months, river flow may fall below levels needed for riverine flora and fauna. Climate-flow data show decreasing minimum flows, with projected reductions of 15-30% in dry seasons [7]
- **Environmental flow compliance:** Local reports indicate some Armenian SHPPs extract more water than permitted, harming spawning fish and aquatic biodiversity. Enforcement of environmental flow requirements is inconsistent
- **Sediment transport disruption:** Pipelines and abstraction structures reduce sediment downstream, affecting river morphology and riparian zones
- **Aquatic ecosystems:** Minor to moderate negative impact in 0.85 km reach between intake and powerhouse; environmental flows essential to preserve ecological connectivity [5]
- **Terrestrial vegetation:** Minimal impact with mitigation; 100 m² landscaping and 20 tree plantings provide minor enhancement

Social Environment:

- Employment: Positive impact—10-15 construction jobs over 12-24 months; 7 permanent operational positions for larger installations
- Community stability: Moderate positive through employment and reduced out-migration
- Energy security: Significant positive through fuel import reduction (~121 tons organic fuel for smaller sites, ~1.1 million m³ natural gas equivalent for larger installations) [2]

Table 2. Annual Environmental Benefits vs. Thermal Generation [2, 6]

Impact Category	Tatev SHPP	Regional Sites Average
CO_2 emissions avoided	~3,500 tons/year	~580 tons/year
NOx emissions avoided	~12 tons/year	~2 tons/year
Water consumption avoided	~5,000 m³/year	~830 m³/year
Fuel import reduction	1.1 million m³ gas equiv.	121 tons organic fuel

5 Discussion

5.1 Economic Viability and Regional Potential

SHPPs in Syunik demonstrate economic viability while offering energy security benefits, though several critical environmental vulnerabilities threaten long-term sustainability.

Fuel savings of 121 tons organic fuel annually for smaller sites and 1.1 million m³ natural gas equivalent for larger installations provide both economic benefits and energy security improvements. With electricity generation costs of 5-8 AMD/kWh significantly below thermal generation at 25-30 AMD/kWh (Sargsyan et al., 2011), small hydropower offers clear economic advantages when environmental externalities are considered.

However, several vulnerabilities warrant attention. Climate change projections indicating 15-30% flow reductions threaten long-term generation capacity. A 20% flow reduction could extend payback periods by 2-3 years and reduce fuel savings proportionally. Conservative financial planning must incorporate larger climate contingencies and adaptive management provisions.

5.2 Environmental Sustainability and Climate Risks

The environmental assessment reveals that Armenian SHPPs face significant ecological challenges beyond those typically documented in international literature. While displacement of 3,500 tons CO_2 annually (larger installations) provides clear climate benefits, several critical risks require immediate attention:

Environmental Flow Compliance: Local reports document that some Armenian SHPPs extract more water than permitted, harming spawning fish and aquatic biodiversity. This operational reality differs from design assumptions and threatens ecosystem sustainability. Enforcement of environmental flow requirements through automated monitoring, regulatory oversight, and penalties for non-compliance is essential [5].

Climate Change Vulnerability: Seasonal flow deficits, already evident in dry months, will intensify under climate change. Reductions of 15-30% in river discharge threaten both economic viability and ecological integrity. Sites must be designed with adaptive capacity: flexible operational protocols, enhanced monitoring, and contingency plans for drought conditions.

Cumulative Impact Concerns: The Vorotan River basin contains multiple existing and proposed hydropower projects. While Papikyan and Papikyan (2024) identified substantial

additional potential, cumulative impacts across the basin merit systematic evaluation. Basin-wide hydrological modeling and coordinated operations ensure aggregate water abstractions remain within sustainable limits.

5.3 Socioeconomic Benefits and Rural Development

Beyond financial returns, SHPPs generate important socioeconomic benefits. Creation of 7 permanent positions per larger installation and proportional employment for smaller sites provides rural economic anchors reducing out-migration pressures. Annual tax revenues of ~22.3 million AMD (Tatev) support public budgets for infrastructure and services.

Fuel import reduction—121 tons organic fuel annually for smaller sites (Papikyan & Papikyan, 2024) aggregated across multiple installations—enhances national energy security and reduces foreign exchange exposure. Construction phase procurement supports local businesses, creating multiplier effects that amplify direct benefits.

However, socioeconomic sustainability requires equitable benefit distribution and community engagement. International experience demonstrates that projects achieve greater acceptance when communities participate meaningfully in planning, share equitably in benefits, and retain voice in operations.

6 Conclusions

This comprehensive economic and ecological assessment demonstrates that small hydroelectric power plants in Syunik region can achieve financial viability while contributing to energy security and climate mitigation, provided that stringent environmental safeguards and adaptive management practices are implemented.

Economic Findings: The Tatev SHPP exhibits favorable performance (IRR 11.73%, NPV 134.5 million AMD, payback 8.2 years), while regional sites demonstrate payback periods of 7-12 years depending on site conditions and discount rates [2]. Fuel savings of 121 tons organic fuel annually for smaller installations and displacement of 3,500 tons CO_2 for larger facilities provide significant economic and environmental benefits. Specific investment costs of $1,800/kW are competitive internationally, with O&M costs of 2-4% CAPEX annually consistent with global benchmarks.

Environmental Findings: While properly designed SHPPs achieve substantially lower impacts than large hydropower and fossil alternatives, critical ecological risks require immediate attention. Seasonal flow deficits, inconsistent environmental flow enforcement, sediment transport disruption, and climate change vulnerabilities (15-30% projected flow reductions) threaten aquatic biodiversity and ecosystem integrity. Mitigation programs costing 0.3% of capital investment can address construction impacts, but operational phase requires continuous monitoring and adaptive management.

Critical Recommendations:

1. **Strengthen environmental flow enforcement** through automated monitoring, regulatory oversight, and meaningful penalties for non-compliance
2. **Implement basin-level strategic planning** to assess cumulative impacts and coordinate operations across multiple projects
3. **Incorporate climate change adaptation** into design and operations, accounting for 15-30% flow reduction scenarios
4. **Ensure stakeholder participation** and equitable benefit-sharing to maintain social license and support rural development
5. **Standardize EIA requirements** including long-term hydrological trends, biodiversity baselines, and monitoring protocols

Broader Implications: This research demonstrates that small hydropower can contribute meaningfully to sustainable development in mountainous regions when projects integrate economic analysis, environmental safeguards, climate adaptation, and inclusive stakeholder engagement. The integrated assessment framework provides a replicable methodology applicable throughout the South Caucasus and comparable developing country contexts. Realizing Armenia's small hydropower potential requires supportive policy frameworks, enforced environmental standards, improved financing access, and institutional capacity building—investments that will position the country as a regional leader in sustainable renewable energy development.

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