



Small Hydropower Investment and Financing Models and Risk Assessment Methods

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Abstract. Small hydropower plays a vital role in mountainous power grids and rural revitalization. However, due to their small project scale, significant cash flow fluctuations, and mismatches between financing terms and hydrological risks, traditional financial evaluation methods struggle to accurately reflect the true risks. This study takes representative run-of-river small hydropower projects in Sichuan as its subject, integrating cash flow simulation, weighted average cost of capital, debt service coverage ratio, conditional value at risk, and default probability models to create a comprehensive risk assessment method for small hydropower investment and financing. Through Copula scenario generation and Monte Carlo simulation, the distributions of NPV, IRR, and DSCR, as well as default probabilities, under different investment and financing models are calculated. Sensitivity and stability analyses are conducted under various scenarios, including water inflow, electricity prices, policies, and contract terms. The results show that PPP, green bonds, and hybrid financing offer advantages over highly leveraged traditional loans in terms of risk-adjusted returns and stability in responding to policy interference. This research provides a methodological reference for optimizing the green investment and financing structure of small hydropower and for risk pricing by financial institutions.

Keywords: small hydropower; investment and financing model; risk assessment; Monte Carlo simulation; conditional value at risk; probability of default

1 Introduction

In recent years, small hydropower has played an increasingly prominent role in distributed energy and green finance systems, but its investment and financing risk characteristics have not changed. Spasenic et al. ^[1] integrated FTA with risk matrix to identify key nodes in the financing process. Akhigbe et al. ^[2] focused on risk stratification and weighting in renewable energy projects. Adhikari et al. ^[3] showed that market, technology and policy uncertainties have a significant impact on the feasibility of hydropower. Shaktawat and Vadhera^[4] proposed comprehensive collaborative risk control, and

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Yüksel et al. [5] used fuzzy multi-criteria decision-making to quantify hydropower investment risks. İpin and Ercan [6] showed that traditional financing channels are difficult to meet long-term capital needs. Akcay [7] formed a risk assessment system under the PPP model based on ANP. Edwidge and Amolo [8] emphasized the role of flexible financing structures and insurance mechanisms. Monteiro et al. [9] found that project returns are driven by scale and cost. Kishore et al. [10] felt that the slow financing system still restricts the development of small hydropower.

2 Investment and Financing Characteristics and Cash Flow Modeling of Small Hydropower Projects

2.1 Project Life Cycle and Cash Flow Composition

To conduct investment and financing risk analysis, an annual cash flow model covering the construction, operation, and decommissioning periods is constructed. Using typical run-of-river small hydropower projects (10–20 MW, annual power generation 40–80 GWh) on the Minjiang and Dadu River tributaries as prototypes, the cash flow consists of construction investment, fixed/variable operation and maintenance costs, debt principal and interest, electricity revenue, renewable energy subsidies, and carbon emission reduction benefits. The annual net cash flow can be written as:

$$CF_t = R_t - C_t^{O\&M} - C_t^{debt} \quad (1)$$

Here, CF_t represents t the net cash flow in year, R_t represents t the total revenue in year, which includes grid connection fees, subsidies, and carbon revenue, $C_t^{O\&M}$ represents t the operation and maintenance costs in year, C_t^{debt} and represents the principal t and interest on the debt repaid in year. Figure 1 shows the cash flow structure and key risk exposures throughout the entire lifecycle.

2.2 Classification and Parametric Description of Investment and Financing Models

As shown in Figure 2, different investment and financing models affect project financial performance through the combined effects of capital structure and cost of capital. Traditional project loans, SPV financing, PPP/concessions, green bonds, and carbon revenue pledging are collectively represented as a combination of equity capital E , interest-bearing debt, D and mezzanine capital M , corresponding to different rates of return and risk levels. The weighted average cost of capital can be written as:

$$WACC = \frac{E}{E + D + M} r_e + \frac{D}{E + D + M} r_d (1 - T_c) + \frac{M}{E + D + M} r_m \quad (2)$$

Where E , D , M represents the size of equity, debt, and mezzanine capital, respectively; r_e represents the required rate of return on equity; r_d represents the nominal debt interest rate; r_m represents the target rate of return on mezzanine capital; T_c and represents the income tax rate. Considering subsidies and tax shield effects, the equivalent cost of capital can be defined as:

$$r_{eff} = WACC - \phi_s S_t + \phi_c T_c \quad (3)$$

Among them, r_{eff} represents the equivalent cost of capital after policy adjustment; S_t refers to t the subsidy income calculated based on installed capacity or power generation in the first year; ϕ_s is the coefficient that converts subsidies into cost reductions; ϕ_c and is the conversion coefficient for the tax shield effect.

2.3 Financing Constraints and Debt Repayment Capacity Indicators

Given a fixed cost of capital, a project's ability to secure debt financing is primarily constrained by several key factors, particularly the debt repayment coverage ratio (DSCR). Commercial banks typically require small mountain hydropower projects to maintain a DSCR of no less than a specific threshold during the loan period. The annual DSCR is defined as follows:

$$DSCR_t = \frac{CF_t^{available}}{DebtService_t} \quad (4)$$

Here, $DSCR_t$ represents t the debt coverage ratio for year, $CF_t^{available}$ which refers to t the cash flow available for debt repayment in year. It equals operating cash flow minus necessary reinvestment and taxes, and $DebtService_t$ represents the t sum of principal and interest payable in year. The constraint is often written as: $DSCR_t \geq DSCR_{min}$, where $DSCR_{min}$ is the minimum allowable coverage ratio, which in practice is often between 1.20 and 1.30. It, along with leverage ratio and interest coverage ratio, determines a reasonable capital structure and debt maturity arrangement.

3 Empirical Analysis and Optimization of Investment and Financing Models

3.1 Comparison of Risk-Return Characteristics under Different Models

Figure 1 shows typical risk-return trade-offs among the models: the high-leverage model F has the highest NPV and IRR, but the probability of default is significantly

higher; PPP and Blended Finance, on the other hand, trade lower returns for higher DSCR quantiles and lower risk.

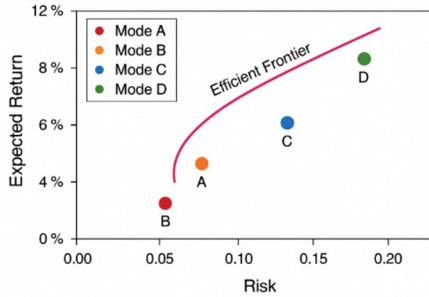


Fig. 1. Scatter plot of risk-return and schematic diagram of efficient frontier for different investment and financing models

3.2 Sensitivity to Uncertain Factors and Scenario Comparison

To distinguish the mutual influence of water inflow and electricity price, the following steps can be taken: First, perform a 3×3 synthesis for the three water inflow scenarios (Dry, Normal, Wet) and the three electricity price scenarios (Low, Base, High). Figure 2 shows the sensitivity and nonlinear superposition effect of hydrological and price shocks under different modes.

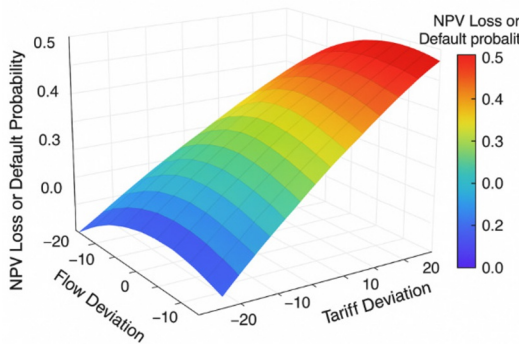


Fig. 2. Three-dimensional surface plot of the impact of key uncertainties

3.3 Robustness Analysis under Policy and Contractual Clause Scenarios

In engineering practice, the feasibility of investment and financing models is highly dependent on the policy environment and contract terms. This section, building upon the baseline simulation in Section 4.2, overlays four policy scenarios: a gradual reduction in renewable energy subsidies, a 5% decrease in feed-in tariffs, and a carbon price increase to 120 CNY/tCO₂. Simultaneously, government guarantees or credit

enhancement mechanisms are introduced. In each scenario, the default probability, expected loss, and risk-adjusted return of model AE are reassessed.

Table 1. Robustness of financing modes under policy and contractual scenarios.

Mode	Scenario	Default Probability (%)	Expected Loss / Equity (million CNY)	Risk-adjusted Return (Sharpe-like)	Comment
A – Traditional	Baseline	7.4	3.2	0.41	Marginal under stress
A – Traditional	Subsidy Phase-out	11.8	5.1	0.27	Sensitive to subsidy removal
B – SPV	Feed-in – 5%	8.9	3.7	0.38	Moderate resilience
C – PPP	Govt. Guarantee	1.3	0.9	0.66	High risk transfer
D – Green Bond	High Carbon Price	2.4	1.2	0.59	Benefits from green premium
E – Blended	All Stress Combined	3.1	1.6	0.53	Most balanced profile

As can be seen from Table 1, under the interference of many policy factors, PPP and Blended Finance have relatively low default probabilities and relatively high risk-adjusted returns, but traditional loan models have performed significantly worse in the face of subsidy reductions and declining electricity prices.

3.4 Model Comparison and Engineering Application Discussion

To verify the actual gains of the comprehensive risk assessment framework, this section compares it with three commonly used methods: static NPV evaluation, expert experience scoring, and DSCR threshold admission rules. When the Sichuan sample power plants are under the same data and policy environment, they will generate different recommendation models. The default situation and benefit results corresponding to various methods under these models will be compared.

Table 2. Comparison of evaluation methods for financing scheme selection.

Method	Selected Dominant Mode(s)	Portfolio Default Probability (%)	Portfolio E[NPV] (million CNY)	Time Requirement (analyst-days)	Data Transparency
NPV-only	F (High-Leverage)	11.6	25.0	2	Low (single scenario)
Expert Scoring	A, B	7.9	21.3	5	Medium (subjective weights)

Method	Selected Dominant Mode(s)	Portfolio Default Probability (%)	Portfolio E[NPV] (million CNY)	Time Requirement (analyst-days)	Data Transparency
DSCR Rule-based	B, C	4.8	22.0	3	Medium
Proposed Integrated Model	C, D, E	2.3	23.4	4	High (scenarios & metrics)
Stress-tested Variant	C, E	1.9	22.8	5	High
Conservative Benchmark	C only	1.5	21.7	3	Medium-High

Table 2 shows that NPV-based methods tend to favor high-leverage allocations and have a higher probability of default. While expert scoring and DSCR rules can reduce risk, they lack systemic scenarios and tail loss characterization. In contrast, the model in this paper combines cash flow simulation, CVaR, and default probability, which can significantly reduce default risk while maintaining returns. Furthermore, it enhances transparency with scenario-based results, providing quantitative support for bank credit pricing and government PPP and green bond screening.

4 Conclusions and Outlook

This study constructs an integrated framework of "cash flow-financing structure-risk indicators-model selection" for small hydropower projects on the Minjiang and Dadu Rivers. The results show that runoff, electricity price fluctuations, and leverage levels are key factors driving NPV volatility and increasing default rates. While high leverage can improve returns, it also amplifies tail losses. PPP, green bonds, and hybrid financing, with smaller returns, achieve higher DSCR percentiles and reduce default probability, exhibiting better overall stability. This framework is applicable to credit pricing, scheme comparison, and project pool management.

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