

Technical, Environmental, and Financial Assessment for the Optimal Sizing of a Run-of-River Small Hydropower Project: A Case Study in Colombia

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Abstract—Run-of-river (RoR) hydropower projects represent a viable, clean, and cost-effective alternative to dam-based plants and provide decentralized power production. However, RoR schemes' cost-effectiveness depends on the proper selection of site and design flow, which is a challenging task because it requires multivariate analysis. In this respect, this study presents the development of an investment decision support tool for assessing the optimal size of an RoR scheme considering the technical, environmental, and cost constraints. The net present value (NPV) from a project perspective is used as an objective function for supporting the investment decision. The tool has been tested by applying it to an actual RoR project recently proposed in Colombia. The obtained results show that the optimum point in financial terms does not match the flow that maximizes energy generation from exploiting the river's available flow. For the case study, the flow that maximizes energy corresponds to a value of 5.1 m³/s. In comparison, an amount of 2.1 m³/s maximizes the investors NPV. Finally, a sensitivity analysis is performed to determine the NPV as a function of the debt rate changes and the electricity prices and the CapEx. Even for the worst-case scenario, the optimal size represents a positive business case with an NPV of 2.2 USD million and an internal rate of return (IRR) 1.5 times higher than the discount rate.

Keywords—Small hydropower, renewable energy, RoR schemes, optimal sizing, financial analysis.

I. INTRODUCTION

IN the last decades, awareness about the need for the responsible use of fossil reserves and increasing penetration of renewable energy sources has favored the development of hybrid energy systems, mainly based on renewable energy sources. In developing countries, the exploitation of renewable sources represents an excellent opportunity for increasing the number of people having access to electricity with an adequate degree of availability and reliability [1]. Hydropower is one of the most used renewable sources of electricity, accounting for more than 16% of the world's net electricity production and more than 71% of net global renewable electricity production. As compared to other renewable energy sources, hydropower is reliable, economical, highly efficient, has a low maintenance cost, and has a large storage capacity [2], [3]. Notwithstanding, dam-based plant construction and operation are costly, can damage and disrupt the upstream and downstream ecosystem, and have catastrophic effects on downriver settlements and infrastructure [4]. Thereof, legislation in many countries,

prohibits further construction of such plants [5].

Considering the current environmental and economic restrictions mentioned above, it is of prime importance to find a way that hydropower, as an electricity source, can be carried out through more reliable, more cost-effective, and safer engineering and financial mechanisms. Small hydropower projects (SHP) can serve this purpose. These are viable, clean, and cost-effective alternatives to dam-based plants and provide decentralized power production. Their relatively low operation and maintenance cost, long life spans, and negligible socioeconomic impacts are highly desirable and have propelled SHP to the center stage of the energy debate [6]. Nevertheless, an investment in an SHP entails a certain number of expenses, extended over the life of the project, and procures some revenues also distributed over the same period. The costs include a fixed component -the capital cost, insurance, taxes other than the income taxes, etc.- and a variable part -operation and maintenance expenses.

In pursuing widespread renewable energy sources in the increasing energy infrastructure, it is essential to address the optimal sizing of an SHP quantitatively. Thus, it is crucial to develop an investment decision support tool that quickly verifies the hydroelectric potential, performing a rapid optimization based on the technical parameters and financial values. In that context, this study analyzes which technical, environmental, and financial aspects need to be considered and how can they be integrated into an investment decision tool that optimizes the design of SHP to maximize investors NPV.

II. LITERATURE REVIEW

The basic principle of hydropower generation is impulse-momentum. Water potential is converted into mechanical energy by rotating the turbine, and mechanical energy is further converted into electrical energy using a generator. The definition of a SHP varies significantly from one country to another. There are three types of SHP. I) Dam-reservoirs, II) Pumped-storage and III) RoR, where water from the natural runoff generates electricity directly; therefore, there is no storage associated with it [7]. This research focuses on the analysis of this type of projects.

In small hydropower RoR schemes, water is diverted from the river by a structure located across the river, called the diversion weir. Water is then passed through the power channel

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up to the forebay tank [8]. A pressure pipe, called a penstock, conveys the water from the forebay to the turbine [9]. Water carried by the penstock directly strikes the turbine blade, followed by the guide vanes to rotate the turbine runner. The turbine's runner is coupled with the shaft, connected with the generator to produce electricity [10]. During the past three decades, research studies on an RoR have been devoted to the plant's optimal design, operation, and performance [11]. Within that research, a primary category is distinguished, which is the focus of the present study; Assessment of the optimal sizing of a RoR small hydropower plant.

The optimization of an RoR has been examined in various studies and it has been framed into three broad sub-categories: A) technical assessment, B) environmental assessment, and C) economic and financial indexes for assessing optimal size. The main contributions in each sub-category are explained below.

A. Technical Assessment

Given that the electro-mechanical equipment (turbines) represents an extensive contribution to the project's economic breakdown, most studies carried out have focused on determining the optimal size of them. Voros et al. [12] present an empirical short-cut design method for selecting the nominal flow rate of hydraulic turbines. Montanari et al. [13] also analyze and develop a model for optimizing a type of turbine through the exploitation of water resources in places with low head. Other studies have considered some other components and the turbine characteristics to determine the plant's optimal size. Almeida et al. [14] introduce a novel methodology where an economic and financial simulation model is used to analyze the project's risk and market variability. Basso et al. [15] proposes an analytical framework to describe the energy production and economic profitability of small RoR power plants based on the underlying streamflow regime.

B. Environmental Assessment

Most RoR hydropower projects commonly adopted the approach to enhance their environmental flow (e-flow), defined as the minimum flow required in the dewatered section of the river to maintain its ecological condition [16]. Magaju et al. [17] presented a model that can potentially integrate e-flows computed according to topographic or hydrologic criteria based on the flow duration curve (FDC) (sub-basin surface, percentage of the design discharge, or similar). Blanco et al. [18] perform a sensitivity analysis regarding power generation's effect, considering a variable environmental flow, both for low water and floods.

C. Economic and Financial Indexes for Optimal Size Assessment

The evaluation of small hydropower plants' investment is made from the base economic criteria, represented by the proposed acquisition's economic indicators. These are static criteria such as the payback time, and the ROI offers only a general view of the value of the planned investment. On the other hand, there are dynamic criteria such as NPV. In these criteria, the time value of money is considered. Most of the studies consider the NPV of the plant as the primary financial

indicator for optimization, since it represents the net difference between all revenues received from the produced electricity and the lifetime cost of the SHP.

III. METHODOLOGY

As explained in the previous section, this study presents the development of a robust computational model of an investment decision support tool that allows evaluating feasibility to determine the optimum size of the SHP. The energy system modeling is made through the combination of empirical and conceptual models [19]. Furthermore, a hybrid approach, meaning the combination of top-down and bottom-up approaches [20], is used to evaluate technical, environmental, and economic parameters. Moreover, the general model itself refers to an optimization model whereby the size of the RoR is optimized by means of an objective function. Fig. 1 summarizes the methodology.

The optimization process follows three steps

- find the installed capacity and the electricity output for a particular design flow,
- calculate the yearly benefits of all the different design flows, and
- select a set of power plants that maximize the NPV based on a combination of the cited constraints.

As a key differentiating element, this study conducts the calculations considering explicitly the turbine efficiency, the hydraulic losses, and the penstock diameter. In like manner, the river's environmental flow is considered and discounted from the disposable flow. This directly impacts the power output of the system. Moreover, static, and dynamic economic indexes are considered for financial optimization. Fig. 1 shows that the optimization model comprises three main blocks: A) Technical-Environmental model, B) The cost model, and C) The financial model. Below a detailed explanation of each block is presented.

A. Technical-Environmental Model

Energy production from hydropower plants is computed daily, considering the environmental flow and technical limitations due to the turbine's technical features. The power output of the hydropower plant, P , in kilowatt (kW), for an instant t , is calculated using (1):

$$P_{t(t)} = (\rho_w * g * H_{net(t)} * Q_{t(t)} * \eta_{t(t)} * \eta_g * \eta_{tr}) / 1000 \quad (1)$$

where $\rho_w, g, \eta_g, \eta_{tr}$ are constants and represent the density of water (kg/m^3), the gravitational acceleration (m/s), the generator, and the transformer efficiency. On the other hand, $H_{net(t)}, Q_{t(t)}, \eta_{t(t)}$ represent the net head or effective water pressure at the bottom of the penstock, the turbine inflow, and the turbine efficiency, respectively.

The turbine inflow is time-dependent and fluctuates according to the natural streamflow, the flow design, the environmental flow, and the minimal technical turbine flow. Likewise, the net head and the turbine efficiency are time-dependent and depend or vary as a function of the turbine inflow, the penstock diameter, and the design flow.

Furthermore, turbine efficiency depends on the type of turbine (e.g., Pelton or Francis). As it is possible to elucidate, (2) has boundary conditions dynamically. Therefore, it cannot be solved analytically. In this respect, numerical integration is

applied by constructing an N-vector of mean daily turbine inflows with a fixed daily integration time step. The series of mathematical formulations used to solve (1) is described step by step below.

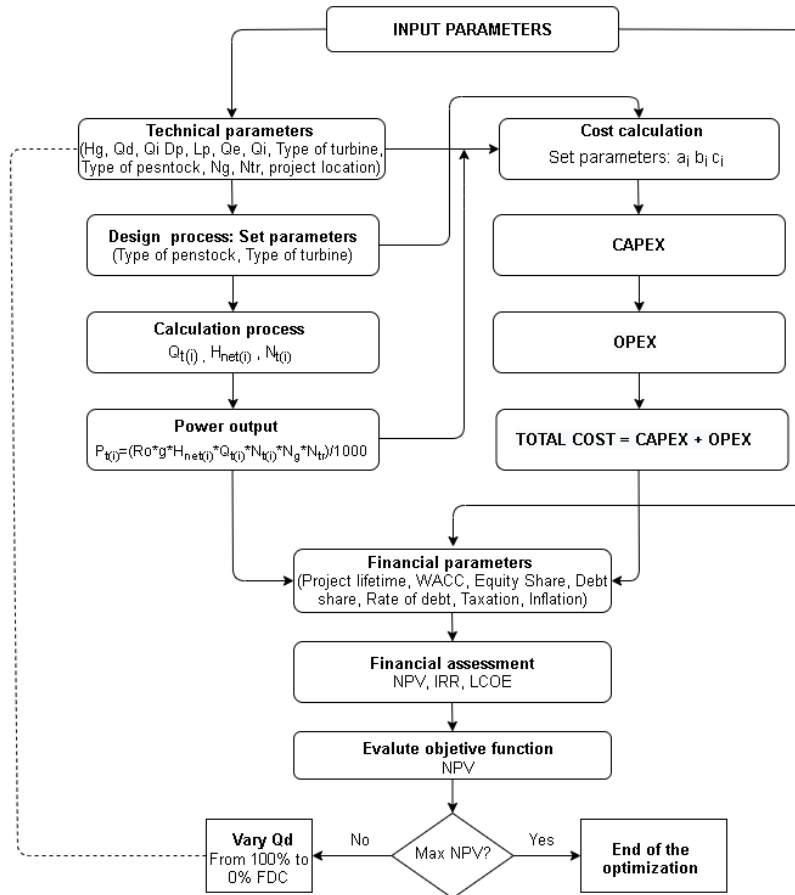


Fig. 1 Flow chart of the optimization process with the technical, cost, and financial models

- Turbine inflow calculation: The process for calculating the turbine inflow is described mathematically by means of (2)-(10). The turbine operates when the water flow is between a minimum and a design flow (Q_{min} , Q_d). Both limits depend on the type of turbine and are specified by the manufacturer. As a rule of thumb, for a Francis turbine, the lower limit is set in 55% of the flow design, while for a Pelton turbine, the limit is set at 35% of the nominal flow rate [21].

$$Q_{u(i)} = Q_{intake(i)} - Q_{environmental} \quad (2)$$

$$\text{if Type of turbine} = \text{Pelton} \quad (3)$$

$$Q_{min} = 0.15Q_d \quad (4)$$

$$\text{else: } Q_{min} = 0.5Q_d \quad (5)$$

$$\text{if } Q_{u(i)} \leq Q_{min} \quad (6)$$

$$Q_{t(i)} = 0 \quad (7)$$

$$\text{elif } Q_{u(i)} < Q_d \quad (8)$$

$$Q_{t(i)} = Q_{u(i)} \quad (9)$$

$$\text{else: } Q_{t(i)} = Q_d \quad (10)$$

- Net head calculation: The net head is involved in (1). It can be calculated by subtracting the system's hydraulic losses (hf) that correspond to the flow rate ($Q_{t(i)}$) conducted to the turbines from the gross head (H_g). The singular losses are related to the enlargement and narrowing, respectively at the entrance and the exit of the forebay tank and to the bend at the beginning of the penstock. These local losses are linked with the motion of the fluid and can be neglected for long pipes [22]. The hydraulic losses (hf) are a function of the length (L_p) and diameter (D_p) of the penstock, the flow velocity ($V_{t(i)}$) at the penstock, which is a function of the turbine inflow, and the friction factor (f). The latter is a function of the type of material (e.g., steel or GRP) and the flow regime inside the pipe (e.g., laminar or turbulent flow).

Generally, the friction factor (f) can be computed by the well-known White-Colebrook equation for a specific flow Reynolds number and a given pipe wall roughness. It is not convenient to use, because its implicit expression in f requires iteration. Since power generation analysis is done for a series of flows over 39 years, with the daily resolution, this iterative process generates a considerable computational cost. For this reason, several approximate explicit counterparts have been proposed. For this study, the equation proposed by [23] is implemented.

As previously introduced, hydraulic losses and flow rates are a function of speed within the penstock. Since the flow depends on the river's conditions and the type of turbine, the pipeline's diameter is a fundamental variable since it determines the speed of the flow. From an economic and construction point of view, it is better to have a small diameter pipe. However, this implies higher flow velocity and, therefore, higher hydraulic losses. The latter translates into a reduction in the electricity generated. On the other hand, a substantial diameter is useful for electricity generation. However, the costs of the pipe increase quadratically with the diameter. Therefore, doubling the diameter implies a 4-fold increase in prices. In this study, for each design flow analyzing and depending on the pipeline's material, the required diameter is calculated to calculate the pipe's maximum velocity below the upper limit. The limits were set based on the author's experience in the feasibility study of hydropower projects and specialized literature. For GRP, the maximum flow velocity is set as 3 m/s, and for steel, the maximum flow velocity is set as 5 m/s [24], [25]. The process for calculating the net head (Hnet) is described mathematically by means of (11)-(25)

$$\text{if Type of penstock} = \text{Steel:} \quad (11)$$

$$V_{max} = 5 \text{ m/s} \quad (12)$$

$$\text{Else: } V_{max} = 3 \text{ m/s} \quad (13)$$

$$A_p = \frac{Q_d}{V_{max}} \quad (14)$$

$$D_p = \sqrt{\frac{4 \cdot A_p}{3.1416}} \quad (15)$$

$$\text{if Type of penstock} = \text{Steel:} \quad (16)$$

$$e = 0.000045 \text{ m} \quad (17)$$

$$\text{Else } e = 0.000029 \text{ m} \quad (18)$$

$$e_R = \frac{e}{D_p} \quad (19)$$

$$V_{p(i)} = \frac{Q_i}{A_p} \quad (20)$$

$$R_{e(i)} = \frac{\rho_w \cdot V_{p(i)} \cdot D_p}{\mu_w} \quad (21)$$

$$f_i = 1.613 * \left[\ln \left(0.234 * e_R^{1.1007} - \frac{60.525}{R_{e(i)}^{1.1105}} + \frac{56.291}{R_{e(i)}^{1.0712}} \right) \right]^{-2} \quad (22)$$

$$h_{f(i)} = f_i \frac{L_p V_{p(i)}^2}{D_p 2g} \quad (23)$$

$$H_{Net(i)} = H_{Gross} - h_{f(i)} \quad (24)$$

- Turbine efficiency calculation: The turbine's performance is characterized by its nominal flowrate, Q_r , which is an explicit indication of its size. Likewise, turbine efficiency depends on the working fluid flow rate and actual turbine characteristics. Voros et al. [12] present an expression that allows calculating Pelton and Francis turbines' efficiency, considering the relationship of the turbine inflow and the design flow. As a novelty, they introduce two characteristic turbine parameters Q_{min} and Q_{max} , representing the fraction of its nominal flowrate corresponding the lower and upper extreme working flowrates, respectively. The empirical expression is proposed for describing the turbine efficiency characteristic curve. Excellent fits to actual experimental data were detected when the proposed expression was used as real turbine data. For each type of turbine (Pelton or Francis), there are maximum efficiencies, design and minimum flow rates, and constants specific to each turbine's efficiency curves. All the technical values are described within [12]. The process for calculating the turbine efficiency (η_t) is described mathematically by means of (25)-(27)

$$\text{if Type of turbine} = \text{Pelton:} \quad (25)$$

$$\eta_t = \eta_{tmax} \left(-0.224 \left(\frac{Q_{t(i)}}{Q_d} \right)^2 + 0.483 \left(\frac{Q_{t(i)}}{Q_d} \right) + 0.741 \right) \quad (26)$$

$$\text{else: } \eta_t = \eta_{tmax} \left(-0.537 \left(\frac{Q_{t(i)}}{Q_d} \right)^2 + 1.047 \left(\frac{Q_{t(i)}}{Q_d} \right) + 0.49 \right) \quad (27)$$

By coupling the previously described steps, (2) is solved using numerical integration for each intake flow. Thus, power output is calculated. The system's rated power is reached when the design flow (Q_d) is derived through the penstock. For this flow, the maximum efficiency of the turbine is achieved. And therefore, the full output power is created. This outcome is one of the primary inputs of the next block. It is the cost model, where the cost of the main components is calculated.

B. Cost Model

The costs of any SHP framed as an RoR project are divided into two categories: capital and variable costs [26]. In the first category, two main components should be considered. I) construction of civil works and, II) electromechanical equipment. The second category refers to the operating and maintenance costs of the two components mentioned above. These can be assumed either as a fixed percentage of the capital expenditures or variables during the project's lifetime.

The maximum power output calculated before is used as an input along with other established variables, such as the

system's gross head. Combining those variables, the project's total cost is estimated through the aggregation of capital expenditures (CapEx) and the operational expenses (OpEx). A non-linear statistical relationship, proposed by [27] and showed through (28) is used for this calculation:

$$CapEx = a * P(MW)^b * H(m)^c \quad (28)$$

where C is the component cost, P means the rated power and H means the gross head. The constants a, b and c are correlation constants which vary depending on the region.

C. Financial Model

The financial evaluation is performed by maximizing an objective function. Therefore, the unknown variable is set as the design flow, and the constraints are the environmental flow, the type of turbine, and the maximum velocity regarding the kind of penstock used. The main inputs are the electricity output integrated in time and the total cost. The NPV method is used to analyze the profitability of investment in an RoR project. Thus, financial evaluation is performed using the discounted cash flow method from a project perspective. The NPV is the sum of the present values of each period's cash flow, plus the initial investment (CapEx). Mathematically, this latter discussion could be described by (29):

$$NPV = CapEx + \sum_{i=0}^T \frac{C_i}{(1+WACC)^i} \quad (29)$$

where C_i means the cash flow at year i, T represents the horizon time (discussed in the case-study), t the analyzed year and WACC the weighted average cost of capital. The projects with negative NPV will be rejected since this means the discounted benefits during the project's lifetime period cannot cover the initial costs invested for the expected risk associated with the project. In comparing a group of projects, the project with the most significant positive NPV is the best one.

IV. CASE STUDY

The case study involves the analysis of a proposed RoR project in Colombia. The proposed project should exploit the stream flows of a small tributary of the Porce River. The catchment area at the intake of the RoR is about 79 km².

The hydrological data consist of 39 consecutive years of mean daily flow data from 1973 until 2011. The mean daily flow data are used to characterize the river's flow regime and constructs the FDC (Fig. 2). At the intake, the discharge fluctuates moderately between values of 0 to 10.5 m³/s, with a mean flow of about 3.11 m³/s. The environmental flow (e-flow) is set as 0.51 m³/s. The gross hydraulic head (Hg) available is set as the difference between the intake and powerhouse. For the case study, it represents a value of 235 m. the GRP pipe on the bench and with an overpass has a length of 1,720 m. The powerhouse is of the superficial type and is equipped with Pelton turbines. The transformer and generator efficiencies are assumed as constants and with values of 0.972 and 0.992, respectively. Fig. 3 shows a schematic plan view of the project.

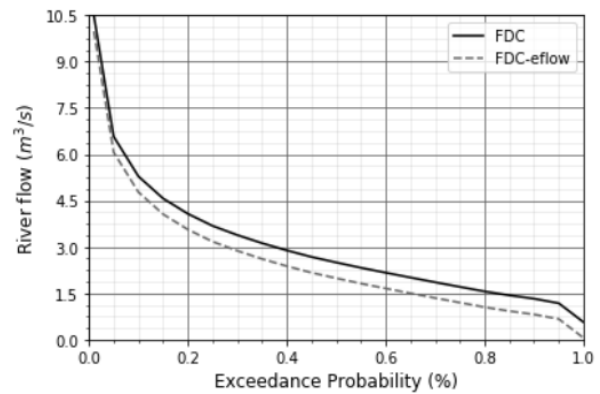


Fig. 2 FDC of the analyzed river

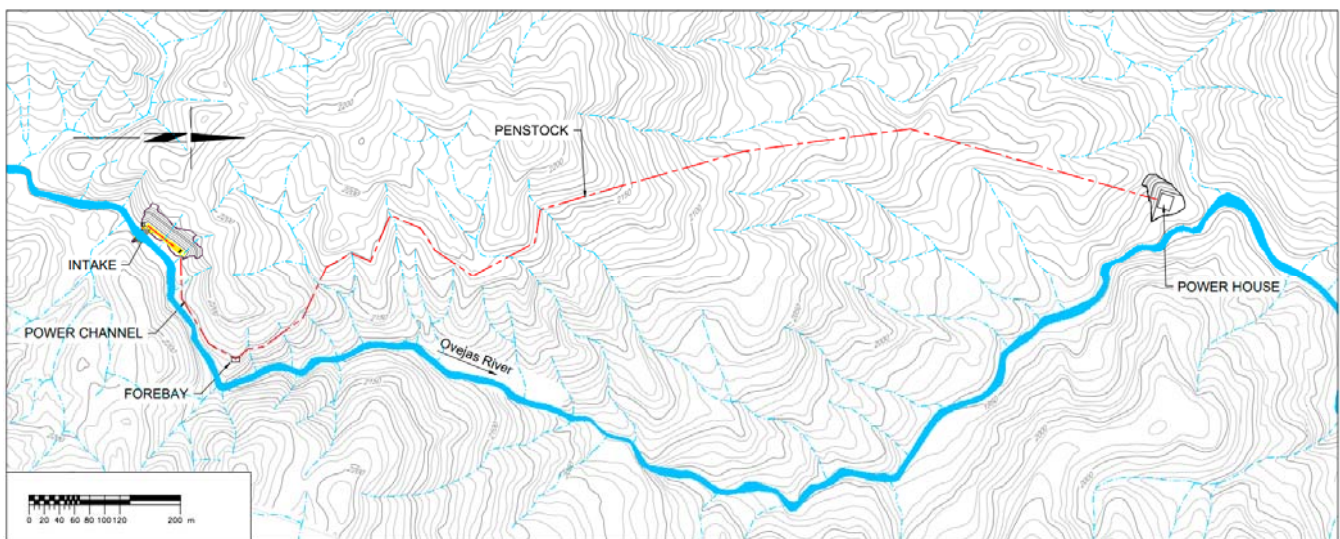


Fig. 3 Top view of the proposed SHP for the case study

The financial evaluation is carried out by constructing the net flows of funds for the project. The tangible benefits associated

with electricity sales are considered. A feed-in tariff scheme is assumed. For the complete assessment of the project, additional financial and fiscal parameters are introduced, like the construction period, tax rate, annual operation and maintenance cost, inflation rate, electricity prices, and project lifetime. For this project, the capital structure is composed of 70% debt and 30% equity. The income statement construction was made considering a depreciation horizon of 10 years and a tax rate of 19%. Besides, regarding the debt, the debt horizon and the rate of debt are assumed as ten years and 7.5 %, respectively.

For the analysis, both CapEx and OpEx are considered. The CapEx was considered the sum of the main components, such as civil works, electro-mechanical equipment, and transmission costs. The OpEx is fixed and represents a 4%/year of the CapEx. To calculate the Weighted Average Cost of Capital (WACC), it is necessary to know the Risk-free return, beta, and ERP. Those values are obtained according to different specialized sources. For the first two variables, a value of 1.07 and 6% are used.

To calculate the incomes, the wholesale electricity price (USD/MWh) is essential. However, the possible fluctuations of those prices are complicated to estimate due to social and political reasons, the increase in renewable energy in the primary grid, and the possible subsidies. Considering that the project's lifetime is 30 years, an initial value, at 2020 of 45 USD/MWh (based on the Colombian Market) is used for the wholesale electricity price. A simple linear interpolation is used

to estimate an inflation ratio, which is applied to both variables at each year of the project evaluation. An inflation value of 3.5% is fixed for all the years

V. RESULTS

A. Preliminary Results

The initial picture of the plant performance is shown in Fig. 4. Fig. 4 (a) shows the behavior of the installed capacity (primary Y-axis), and the capacity factor (secondary Y-axis) of the evaluated points are illustrated, depending on the design flow. The total variation interval, expressed in terms of the plant capacity, plant factor, ranges from 0 MW to 20.7 MW and from 0.18 to 1, respectively. As expected, due to the linear relationship among the variables, the higher the flow, the bigger the plant's power. However, the capacity factor behavior is inversely proportional because of the water resource's depletion at the source to serve the plant's high capacities. Capacity factors represent the ratio between the annual output and the nominal capacity. For a RoR project, plant factors more significant than 0.50 and less than 0.80 are considered adequate [28]. Thus, it is expected that the optimal flow is in the range of 1.9 m³/s to 4.7 m³/s. Fig. 4 (b) shows the behavior of the electricity output (primary Y-axis) and the capacity factor (secondary Y-axis) of the evaluated points are illustrated, depending on the rated power.

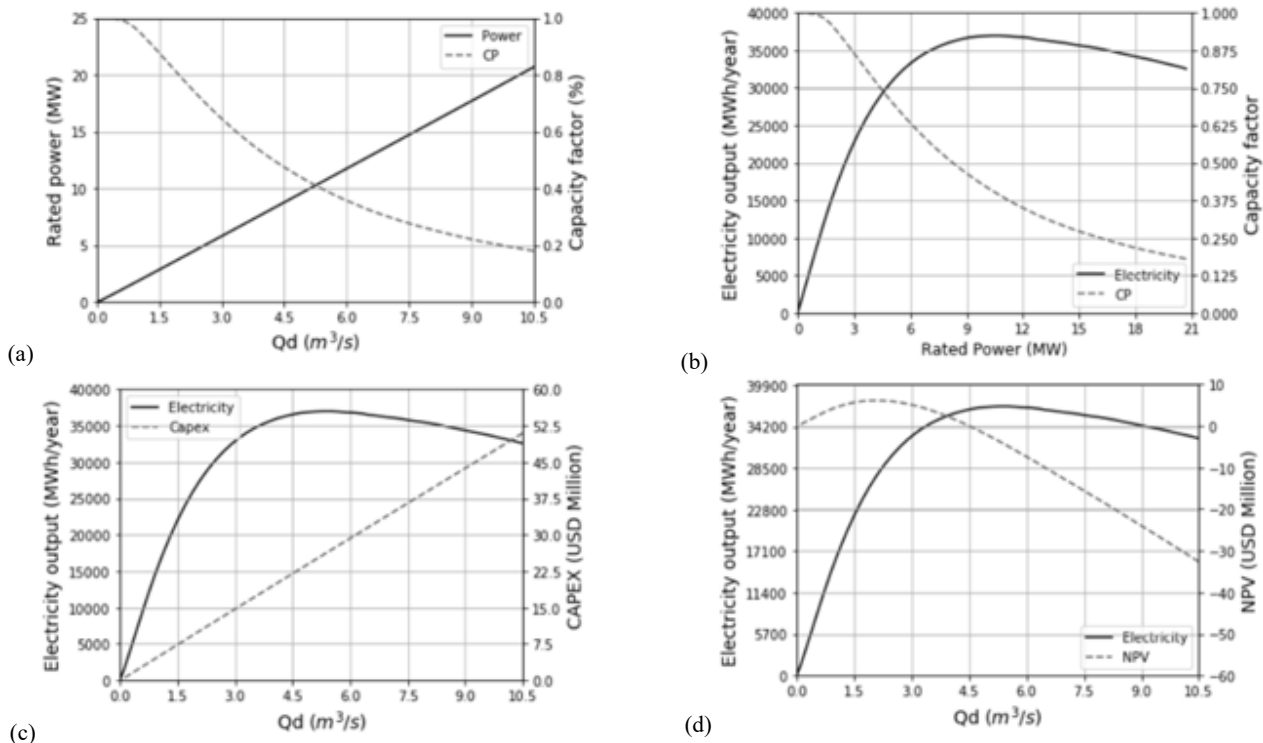


Fig. 4 Primary optimization results

Fig. 4 (b) shows that neither of the two variables has a linear dependency. Energy production increases as installed capacity increases because the more significant the installed capacity,

the larger the turbines and, therefore, the river's high flow regime is exploited more efficiently. However, the curve exhibits an inflection point where electricity production begins

to decrease. The turbines' installed capacity is such that it cannot operate during low flows period since the flow to be derived far from the minimum turbine inflow that guarantees safe and reliable operation of the equipment.

The maximum electricity output of 36975 MWh/year is reached when the design flow is equal to 5.3 m³/s, representing a rated power of 10.40 MW and a capacity factor of 0.41. As will be discussed below, the flow implies the highest energy generation does not mean the plant's optimum point. Fig. 4 (c) compares the electricity output (primary Y-axis) and the CapEx (secondary Y-axis) depending on the design flow. While the cost of capital (CapEx) decreases as the installed capacity is reduced, which occurs due to the reduction of the design flow, the generation of energy has an inverse behavior. For a flow range between 10.5 m³/s and 5.3 m³/s electricity production increases. However, from the lower limit of the previous range, the generation begins to fall with a gradual slope until it reaches a value of 2 m³/s, representing an installed capacity of 3.6 MW and an electricity generation of 25,915 MWh/year. From this point on, the electricity generation decreases considerably, which means there is a non-optimal exploitation of the plant's water resource.

Fig. 4 (d) shows the behavior of the electricity output (primary Y-axis) and the investor NPV (secondary Y-axis) depending on the design flow. The NPV curve also shows nonlinear behavior. From the investors point of view, the range of flows in which the project begins to be financially attractive coincides with the range previously identified. The plant factors fluctuate between values considered adequate according to the literature. These cover a range of flows between 1.9 and 4.3 m³/s, which correspond to values between 35% and 143% of the multi-annual average flow. From a design flow of 10.5 m³/s, representing the maximum flow of the river duration curve, to the upper limit of the range described above, the electricity production only marginally increases while adding extra cost to the construction and the O&M of the project. That means that both capital and operational expenditures for the higher rated power exceed the revenues from the incremental power production.

B. Selected Design Flow

The selected design flow is the streamflow that maximizes the objective function (the investors NPV). The corresponding optimal design flow is equal to 2.1 m³/s, a streamflow that is exceeded 60% of the time. Thus, the degree of exploitation of the available water resources allowed by the optimal design flow is very high, as evidenced by the capacity factor obtained, with a value of 0.78. For this flow of 2.1 m³/s, the rated power of the RoR is 4 MW, and the annual electricity output reaches a value of 27,567 MWh. Regarding the economic values, the reached NPV is USD 6.4 million, the IRR is 18%, and the payback time is eight years.

Given the NPV of USD 6.4 million, it is possible to conclude that the analyzed case is a positive or profitable business model. Besides, the IRR is 2.5 times higher than the WACC. In respect thereof, the optimized RoR project represents a desirable rate of return for investors. Fig. 5 shows the behavior of the

comparison between the free cash flow of the project and the cumulative cash flow.

Regarding Fig. 5, it is essential to highlight that the project is in the execution stage during the first three years. Thus, this initial stage represents a negative cash flow. However, as of the fourth year, when electricity generation begins, a constant, growing, and positive cash flow is presented. Since the operation's marginal costs are meager given that the primary fuel is water, which is free and renewable, the investment and initial capital injection is recovered in year 8, where the breakeven is reached (from a pay-back time perspective). From this point, the project only leaves profits for the investors.

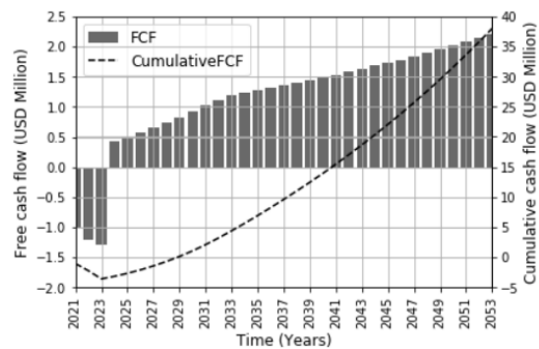


Fig. 5 Comparison between the FCF and the Cumulative FCF of the investors

C. Sensitivity Analysis

For the current case, capital incomes are due to electricity sales. Contrarily, expenses are associated with the initial investment (CapEx) and Operational costs (OpEx). A sensitivity analysis is performed to determine the impact of the change in some of the variables and its effect on the project's profitability. The used methodology consists of simultaneously changing both variables, where one of the variables is related to the income (electricity sales) and the other to the operational costs (CapEx). Then the leading financial indicator (NPV) is calculated for each possible combination. Both variables are sensed up to 15% above and below the current price in every combination. This latter is done with intervals of 5% up and down.

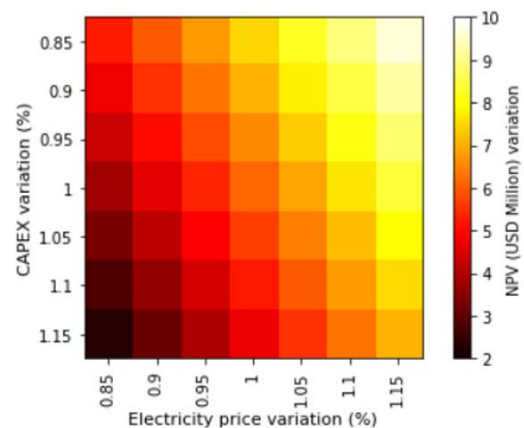


Fig. 6 Relationship among NPV, Electricity and CapEx value fluctuation

Based on the results shown on Fig. 6, it is essential to mention that even for both variables' most unfavorable combinations, the NPV is positive. If the electricity price is 15% below the expected market value and the CapEx investments are 15% higher than the used values, the NPV is still positive, i.e., USD 2.33 million. This latter means that the investment risk is covered in the worst of conditions since the IRR value is 1.5 higher than WACC. On the contrary, if the variables analyzed are inverted, the price of energy increases by 15%, and the initial cost of the investment decreases in the same proportion, the business case rises considerably, and the value of the NPV is USD 9.67 million.

The levelized cost of electricity (LCOE) is the current total cost value of building and operating a power-generating facility over its entire useful life [29]. Lately, the LCOE has become a commonly used tool for cost comparison and has been useful to government and investors in their decision-making processes.

As discussed, hydropower is capital-intensive and has low O&M costs and no fuel costs. Thus, LCOE and NPV are very sensitive to investment costs and interest rates. Since the project capital structure is fixed, the only way to vary the discount rate (WACC for the present analysis) is by changing the cost of debt. To understand the previous discussion's impact, a sensitivity analysis is carried out, varying the cost of debt from a value of 3% to 10% with intervals of 0.5%.

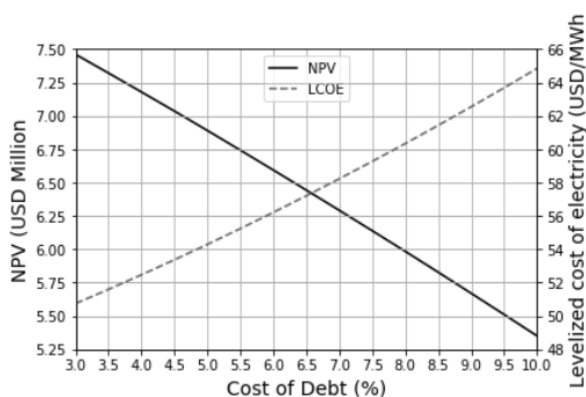


Fig. 7 Sensitivity of the NPV and LCOE to different debt costs

Fig. 7 shows that the lower the cost of debt the higher the NPV and the lower the LCOE. For the scenario where the debt cost is equal to 3%, the NPV and the LCOE obtained are USD 7.85 million and 50.7 USD/MWh, respectively. In the extreme case in which the debt cost value is 10%, the NPV decreases to USD 5.35 million and the LCOE reaches a value of 65 USD/MWh

VI. CONCLUSION

The present research develops an investment decision support tool to assess the optimal size of RoR scheme. The methodology and the tool itself are applicable and scalable through regions and economies. Its flexibility and generality make it a useful tool for selecting the optimal design flow in practical applications as demonstrated by the case study presented in the research.

It is concluded that the acquisition and cost of debt depend on the specific project and the country where it is deployed. In emerging countries such as the one exposed the cost of debt can considerably affect the competitiveness (measured via the LCOE) of the electricity source, and therefore the project's financial viability. Furthermore, the results of this research study allow to show that it is paramount to consider the turbine efficiency, the hydraulic losses, and the penstock diameter to assess the economic feasibility of an RoR project, before spending substantial sums of money. Finally, the present analysis was performed for a typical case where the RoR project is connected to the primary grid. However, the optimal design flow's main outcome could change if the analysis is performed for a non-grid connected project. Therefore, as part of the ongoing research, it is recommended to analyze this kind of scenario in the short-term.

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