DYNA
http://dyna.medellin.unal.edu.co/

UNIVERSIDAD NACIONAL DE COLOMBIA

Methodology to rehabilitate hydroelectric power plants

Marcos Aurélio de Araujo [a], Jorge Javier Gimenez Ledesma [a] & Oswaldo Hideo Ando Júnior [a,b]

[a] *Programa de Pós-Graduação Interdisciplinar em Energia e Sustentabilidade (PPGIES), Universidade Federal da Integração Latino-Americana (UNILA), Foz do Iguaçu, Paraná, Brazil. marcos.araujo@aluno.unila.edu.br, jorge.ledesma@unila.edu.br*
[b] *Unidade Acadêmica do Cabo do Santo Agostinho, Universidade Federal Rural de Pernambuco, Recife, Brazil. oswaldo.junior@pq.cnpq.br*

Received: February 24th, 2022. Received in revised form: July 21st, 2022. Accepted: August 10th, 2022.

Abstract
Repowering the Brazilian hydroelectric park is a way to expand the use of energy from hydro sources, even in a scenario where the options to build new projects are increasingly restricted. Several technical and economic aspects must be considered when evaluating the feasibility to carry out a repowering process, where indicators are considered to choose the best option. The repowering suggests the addition of assured energy, however, electromechanical equipment improvement may occur simultaneously with automation systems. Sizing is generally precise for a hydropower plant and there is no need for repowering so that the project can increase its useful life, consequently, rehabilitation is recommended. This paper shows a methodology to evaluate intervention alternatives in a project, as well as a rehabilitation case study for the *Marimbondo* Hydroelectric Power Plant.

Keywords: methodological approach; hydropower rehabilitation; repowering and expansion; modernization process.

Metodología para la rehabilitación de centrales hidroeléctricas

Resumen
La repotenciación del parque hidroeléctrico brasileño es una forma de ampliar el uso de la energía de origen hidráulico, más aún en un escenario en el que las opciones de construcción de nuevos proyectos son cada vez más restringidas. A la hora de evaluar la viabilidad de llevar a cabo un proceso de repotenciación hay que tener en cuenta varios aspectos técnicos y económicos, en los que se consideran los indicadores para elegir la mejor opción. La repotenciación sugiere la adición de energía asegurada, sin embargo, la modernización del equipo electromecánico puede ocurrir simultáneamente con la adición de sistemas de automatización. En el caso de una central hidroeléctrica, el dimensionamiento está generalmente bien realizado y no hay necesidad de repotenciación para que el proyecto pueda aumentar su vida útil, entonces se recomienda la rehabilitación. En este trabajo se presenta una metodología para evaluar las alternativas de intervención en un proyecto, así como un estudio de caso de rehabilitación de la Central Hidroeléctrica de *Marimbondo*.

Palabras clave: enfoque metodológico; rehabilitación hidroeléctrica; repotenciación y ampliación; proceso de modernización.

1 Introduction

New investments in hydroelectric systems will come due to the advance of technology in several areas of energy generation, with specifications to use recent technological solutions. New ventures must comply with current legislation, use efficient equipment, be environmentally friendly, and be aware of innovations. Some examples of these innovations are the use of Computational Fluid Dynamics (CFD) and Geographic Information System (GIS). CFD optimizes the geometry of hydraulic turbines and fluid flow into a hydraulic circuit, which promotes better performance; while GIS makes easy mapping and identifying some hydraulic potential [1].

Technological innovations can also be used in hydroelectric studies when repowering or modernizing a hydroelectric plant with more than 25 years of operation. So, increasing the useful life of these projects promotes some reduction on maintenance costs and an increase in energy generation.

A 25-year-old Hydro Power Plant (HPP) or older presents some equipment deterioration due to time lag, and sizing obsolescence, hence, there are changes in power parameters [2]. During rehabilitation, repowering and modernization

How to cite: de Araujo, M.A., Ledesma, J.J.G. and Ando Júnior, O.H., Methodology to rehabilitate hydroelectric power plants. DYNA, 89(223), pp. 114-120, July - September, 2022.

planning, alternatives are elaborated, then cost and benefit analysis are carried out, as well as the results are compared, and the best option is chosen [3].

Another way to analyze energy potential of water resources is to evaluate which are the possibilities to build a Reversible Hydroelectric Power Plant (RHP). In this category of hydroelectric utilization, there is a pumping water system among reservoirs, which aims at storing extra energy, to be used in periods of high demands. The challenge for this category of project is related to location, and reservoirs must be built close to each other horizontally, but separated vertically. The selling price of energy for a viable RHP must be 30% higher than that purchased to be used for pumping [4].

The concept of rehabilitation suggests that hydroelectric and electromechanical equipment of a hydropower plant are repaired so that they can work like a new one. In repowering, the generating unit undergoes changes in its initial design, and its energy potential has increased. The addition of a generating unit can also occur by filling in specially designed and purpose-built empty wells. In modernization, technological updates are made to the entire enterprise, and in this modality, automated systems are installed, in order to provide greater efficiency and control to the process. A viable intervention in an enterprise demands that produced energy values must be lower than those ones offered in the electricity supply market.

According to *Empresa de Pesquisa Energética* (EPE) [2], studies on hydropower plant repowering and modernization have contributed to: (*i*) identify effects of deterioration and estimate the costs of using obsolete machinery; (*ii*) additional gains after rehabilitation; (*iii*) required investments; (*iv*) economical evaluation of benefits; and (*v*) technical and regulatory debates.

The world's hydropower capacity in 2020, according to the Hydropower Status Report [5], was 1,330 GW, however, energy requirement from water resources in 2050 will be 2,600 GW. This information suggests that in the coming years, there will be a need to build as much capacity as hydroelectric plants. According to this scenario, it is clear the importance of hydropower for energy security, which justifies future investments in this energy source, both for construction and rehabilitation.

Thus, this study aims at suggesting a methodology to indicate the necessary actions to rehabilitate hydroelectric power plants. Energy from these generating units contributes to sustainability, however, the equipment wears out over time, and this which affects its efficiency. Besides these deteriorations, the reservoir silting is a concern that should be observed, because, depending on the situation, a construction or an improvement of a bottom discharge system may be required.

So, this work is a tool to assist in feasibility studies of rehabilitation projects for hydroelectric power plants.

2 Literature review

Literature research and a selection of relevant papers were carried out to support the writing of this paper. Therefore, "*Methodi Ordinatio*" and "*ProKnow-C*" methods were applied. The first one was proposed by Pagani Kovaleski and Resende [6], whose resource allows performing a systematic review of literature.

The "*ProKnow-C*" method was developed at *Universidade Federal de Santa Catarina* (UFSC), under the coordination of Professor Leonardo Ensslin, from the *Laboratório de Metodologia Multicritério de Apoio à Decisão* (LabMCDA) [7,8]. The bibliographic reference selection methodology "*ProKnow-C*" is a structured construction process, consisting of a series of sequential procedures.

Using these methods, relevant papers were analyzed, filtered, and selected during this research. After this, 1,290 papers were selected to be used in the ranking algorithm by the number of quotes, and finally the 110 most cited papers were selected.

According to Adhikary and Kundu [9], lifespan extension of Small Hydropower Plants (SHP) is a critical task as it involves different factors and policies. Based on this paper, the authors highlight as a challenge the lack of experience, no standard design reference, the unavailability of initial SHP documents, copyright issues, reluctance to accept changes, and the difficulty of financial feedback.

The evolution of hydraulic turbine designs has optimized electricity production, as well as automated operation of these plants has promoted greater reliability in the process. Agugliaro *et al* [10] report that, despite the time of traditional turbines, there is still opportunity to research in this area, which can result in greater optimization of this technology, contributing to meet future demands for electricity.

Mishra, Singal and Khatod [11] point out that technical and economic feasibility are the most significant indices in hydroelectric projects. As for the costs, electromechanical equipment is the most relevant. The authors recorded that a correlation was made among equipment costs and the design parameters of a Small Hydropower Plant. Data from this research can be used to evaluate the costs of projects in this area.

Ogayar, Viddal and Hernandes [12] developed a method to obtain the cost of rehabilitation and renovation of each of the possible structures or equipment that can compose a Small Hydropower Plant, which allows creating an index that relates cost per kilowatt, thus making it possible to compare different plants. This method was developed by the authors and applied by the government of Andalusia region in Spain to determine which dams the rehabilitation process was feasible. Thus, four from nineteen plants were chosen to be evaluated and rehabilitated.

The hydropower plant will only undergo rehabilitation if it is economically feasible. Rahi and Kumar [13] used the Net Present Value (NPV) method to determine feasibility of two repowering options for the *Chabba* plant in India. Hydrological history was critical in this study to estimate power production capacity of the plant and hence its financial feedback.

Haguma, Leconte and Krau [14] evaluated the climate change impact on the rainfall regime of Manicouagan River, a province of Quebec, in Canada. Also, based on Net Present Value analysis, they compared scenarios of expansion or repowering of hydroelectric power plant generating units, and concluded that this option is the most viable.

According to three case-studies, Veiga and Bermann [15] demonstrated some repowering projects of hydroelectric plants. And according to this study, the authors classified repowering in Minimum, Light and Heavy. In minimum repowering, three was a 2.5%-increase in power, and, in the medium one, there is a 10%-increase and in the heavy repowering, the gains are 23.3%.

Machado [16], in his literature review "*Considerações sobre repotenciação e modernização de usinas hidrelétricas*", published by EPE, shows that repowering and modernization of Brazil's hydroelectric park will contribute to an increase of only 0.5% in capacity. Thus, the interventions goals in old hydropower plants should be to preserve the existing capacity and increase the useful life of these enterprises.

As pointed out by Roussille *et al* [17], 50% of hydroelectric plants in operation in Brazil have been working for 20 years or more, such as the *Ilha Solteira* Plant example. There, operational problems have increased long years, since they caused some increase on its vibration level. This resulted in some wear on moving parts of the generator set. After the plant's rehabilitation, vibrations decreased by 40%, providing a 20% increase in the generated energy and an increase in its useful life.

Marcelo and Camargo [18] described how was challenging to modernize the *Cachoeira Dourada* HPP as they aimed at sharing their experiences. The main difficulties were: (*i*) Schedule delays; (*ii*) 10%-cost increase; (*iii*) Charges made by regulatory agencies; (*iv*) Lack of manufacturing and assembly drawings and details; and (*v*) Field rework.

3 Materials and methods

The proposed procedure will be done by indexes comparison, to create a methodology to compare alternatives for hydroelectric projects rehabilitation. Therefore, some parameters will be analyzed and placed in a table, and results of calculations are ranked. The alternatives are presented in an increasing order, with the best option at the top of the list.

Both EPE [2] and Djalma Caselato [3] propose equations to evaluate alternatives for hydroelectric plant rehabilitation. These equations provide values for each scenario, which after ranking can indicate the best option. Thus, eq. 1 is used to obtain the turbinable power value.

Turbinable power:
$$P_t = \gamma_a * Q_t * H_l * \eta \ \ [W] \qquad (1)$$

Where: ρ_a: Specific mass of water = 997 [kg m^{-3}]; g: Gravity acceleration = 9.81 [m s^{-2}]; γ_a: Specific weight of water ($\rho_a * g$) [N m^{-3}]; Q_t: Turbinable flow = Q_{max} [m^3 s^{-1}]; H_l: Net fall height [m] e η: Efficiency [%].

The availability index of generating units is obtained by eq. 2.

Availability factor:
$$f_d = (1 - T_{EIF}) * (1 - T_{EIP})[\%] \qquad (2)$$

Where: T_{EIF}: Equivalent forced unavailability rate [%] and T_{EIP}: Equivalent rate of scheduled unavailability [%].

The Equivalent Forced Unavailability Rate (T_{EIF}) represents the time that the hydroelectric plant was stopped for unscheduled maintenance. The Equivalent Rate of Scheduled Unavailability (T_{EIP}) represents the scheduled outages. Typical values for the availability factor vary from 0.91 to 0.94, and below these values, it may be suggested plant's rehabilitation. T_{EIF} and T_{EIP} indexes, when reduced, can increase the generation capacity.

The Capacity Factor (f_c) measures in percentage the relation between the average power produced in a year and the installed power. It (f_c) is obtained by eq. 3.

Capacity factor:
$$f_c = \frac{P_t}{P_i * f_d}[\%] \qquad (3)$$

Where: P_t: Turbinable power [W]; P_i: Installed power [W] and f_d: Availability factor [%].

The Annual Generated Energy (E_a) corresponds to the produced energy by the generating unit in one year, and it was obtained by eq. 4.

Annual generated energy:
$$E_a = \frac{P_t * f_c * \Delta_t}{1000000}\left[\frac{MW}{year}\right] \qquad (4)$$

Where: P_t: Turbinable power [W]; f_c: Capacity factor [%] e Δ_t: 24 hours * 365 days = 8760 [h].

In repowering, the Efficiency factors (η_{tg}), Net fall height (H_l), Turbinable flow (Q_t), and Capacity factor (f_c) can be changed to values that provide an increase in generated energy.

Efficiency tends to improve as there is an advance on design and production techniques for equipment, turbines and generators. It is also possible to decrease load losses and premature wear of hydraulic circuit by using modern materials. The use of new technologies, when compared with those manufactured in the 1960s, can increase energy production capacity, using the same amount of water resource.

The performance of a generating unit depends on the natural deterioration of machines, represented by energy production percentage at a given period. The generation performance over time is shown in Fig. 1, considering that a hydroelectric plant is: (*i*) produces as a new one; (*ii*) there is no repair; (*iii*) it is restored; (*iv*) repowered; and (*v*) modernized.

The age of the plant, associated with the machine wear and its technological lag, contributes to power production decrease. In 1920, the efficiency of turbine-generator set was about 80% and by 2020, this figure increased to 92%. According to the graph, the ideal period to its rehabilitation would be 25 years. The graph also shows that there is a 10%-gain in modernization of a hydropower plant capacity and 5% in its repowering [2].

Besides keeping the enterprise active, rehabilitation must be economically attractive, so, the Cost Benefit Ratio (CBR) indicator is analyzed. CBR is the ratio between production cost and available energy. Firstly, the Capital Recovery Factor (CRF) in eq. 5 and the Project-Related Costs (CT) in eqs. 6 and 7 should be calculated to obtain CBR.

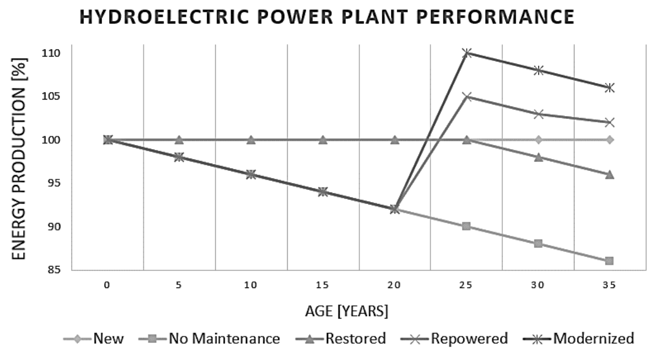

Figure 1. Hydropower plant performance.
Source: The authors, based on [2].

Capital recovery factor:
$$CRF = \frac{j_a * (1 + j_a)^z}{(1 + j_a)^z - 1} \quad (5)$$

Project-Related costs:
$$CT = (C * CRF) + (COM * \Delta_t * \Delta E_f)\ [\$] \quad (6)$$

Cost-benefit ratio:
$$CBR = \frac{CT}{\Delta_t * \Delta E_f} \left[\frac{\$}{MWh}\right] \quad (7)$$

Where: j_a: Annual interest rate is 8 %; z: Economical useful life of a 35-year plant; *C*: Cost of expansion works plus interest [$]; *COM*: Annual cost of operation and maintenance of 1.96 [$/MW/h]; Δ_t: 24 hours for 365 days and 8760 h; e ΔE_f: Firm energy addition [MW/h].

Djalma Caselato [3] adds to these calculations Cost of Non-Generated Energy equation (C_{NGE}). The enterprise that, to fulfill a contract, has to buy some energy has an extra expense, and the annual cost of non-generated energy is obtained by eq. 8.

$$C_{NGE} = \Delta_t * V_{EP} * P_{GNS} * F_{year} * CRF * 10^{-3} [\$] \quad (8)$$

Where: V_{EP}: Energy purchase value [$/MWh]; P_{GNS}: Guaranteed power not supplied [MW]; and F_{year}: Fraction of the year of non-supplied power.

A spreadsheet is created according to the calculations results, and a classification of alternatives is made to choose the lowest cost-benefit. A flowchart is shown in Fig. 2 to ease the understanding of the methodology, and to indicate the steps that must be followed.

Following this flowchart, the first step is to inspect the hydropower plant, and choose the decision criteria to obtain data, settings and parameters. Based on this information, output, availability and marginal cost of operation are analyzed. If output and availability are low and marginal cost of operation is high, there is an indication that the hydropower plant needs some intervention. In the second step, there is a criteria weighting to show the reasons for such decision, then a concept is given for the plant, where the current status of the equipment is compared to a new one, which can be: (*i*) normal; (*ii*) run-down equipment; or (*iii*) under risk. The third step is to create scenarios and fill them with the following parameters: (*i*) need for improvements;

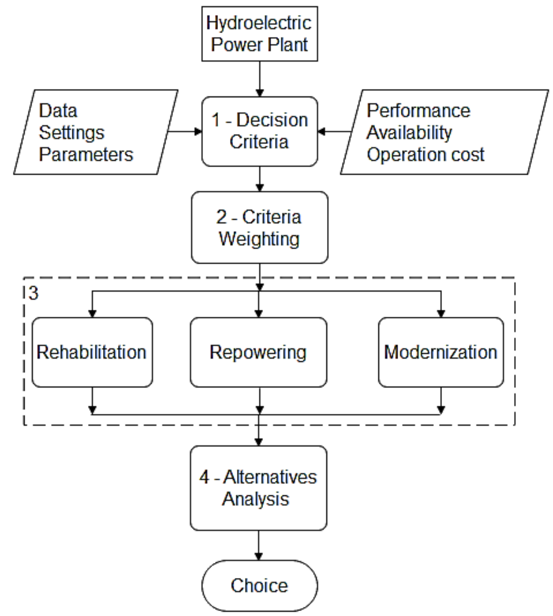

Figure 2. Flowchart to choose the scenario with the best performance.
Source: The authors.

(*ii*) intervention costs; (*iii*) power increase; (*iv*) costs associated with the project; and (*v*) cost-benefit ratio. In the fourth step an analysis was carried out to choose the alternative that presents the lowest cost-benefit.

4 Case study

There are some indications such as a decrease trend on yield descriptions and an increase trend on downtime, which show that a plant needs to be restructured. In relation to a counterfactual scenario, rehabilitation should reduce maintenance services, improve performance, as well as provide safety during an operation.

A theoretical proposal will be used for *Marimbondo* HPP rehabilitation as a case study in this paper. This plant started operating in 1975 (so, in 2021, it was with 46 years). Thus, it has become a modern version of another old plant from the past, whose power was about 200 times less than this modern one. The plant belongs to *Furnas Centrais Elétricas* in *Rio Grande* River, in *Paraná* River Basin, between *Icém* (SP) and *Fronteira* (MG) cities. So, when the diversion channel gates were closed, the 30-meter-high waterfalls were submerged [19]. Data from *Marimbondo* HPP are shown on Table 1.

Table 1.
Data from *Marimbondo* HPP

***Marimbondo* HPP data**	
Installed capacity	1,440 [MW]
Generating units	8
Turbine type	Francis
Fall height	60 [m]
Tributary flow	1,695 [m^3s^{-1}]
Performance	87 [%]
Availability factor	90.24 [%]
Capacity factor	49 [%]
Firm energy	636 [MW]
Annual energy	2,731,838 [MW/year]

Source: [2].

The design constraints must be observed during a rehabilitation analysis in order not to analyze a scenario known as technically or economically unfeasible. So, constraints during *Marimbondo* HPP rehabilitation are [20]:

(i) The upstream level of the plant ranged to 445.73-meter high due to the *Gumercindo Penteado* bridge (BR-364), in upstream of the plant;
(ii) Minimum flow rate of 312 m^3s^{-1}, due to possible damage to ichthyofauna;
(iii) Minimum turbine flow of 1,100 m^3s^{-1}, from October to April (IBAMA Ordinance Nº 60, on October 17th, 2003) to avoid risks during fish spawning period;
(iv) Maximum flow rate of 8,000 m^3s^{-1} due to BR-153 highway bridge located downstream of the plant;
(v) Discharge flows above 6,300 m^3s^{-1} need to be always inspected due to possible flooding;
(vi) In a discharge flows above 6,000 m^3s^{-1}, there must be communication with those responsible workers for a stone quarry and a sand port downstream of the plant;
(vii) When discharge flows are above 10,000 m^3s^{-1}, a downstream commercial area may be flooded;
(viii) Discharge flows above 12,000 m^3s^{-1} may cause flooding at an alcohol plant; and
(ix) Maximum variation rate is 2,000 m^3s^{-1}.

Naturally, *Marimbondo* HPP has already undergone several maintenance interventions, whether they are preventive, corrective or predictive. This must have increased reliability, availability and safety of a company. During the corrective maintenance, the focus is on correcting faults, while on preventive maintenance, the focus is on preventing the occurrence of faults, and in predictive maintenance, the focus is on monitoring sensors and intervening if necessary [21]. While, maintenance aims a keeping availability; rehabilitation aims at reviewing the design parameters and study a way to operate the plant like a new one.

There was no obsolescence in sizing the installed power of *Marimbondo* HPP, neither empty wells to be added to power generating units, consequently, there is no need for repowering. The reservoir drawdown is another fact that occurs, since it is a variable to be analyzed during rehabilitation and caused by water deficit. These events allow a plant to stop producing some assured energy, forcing the electric sector to make up and use the energy reallocation mechanism [22].

Based on the equations presented on "Materials and methods" section and on data of *Marimbondo* HPP obtained from EPE [23], Table 2 shows the general costs of an enterprise, and Table 3 shows the results of the economic evaluation for rehabilitation, repowering and modernization cases.

Table 2.
General Cost Estimation

Costs	
Cost of turbines and generators [US$]	$320.119.338,24
Cost of electrical equipment [US$]	$30.218.237,75
Total direct cost [US$]	$350.337.575,98
Indirect costs [US$]	$28.377.343,14
Final investment cost [US$]	$378.714.919,12

Source: [23], p. 20.

Table 3.
Economic evaluation

Economic evaluation	Rehabilitation	Repowering	Modernization
Need for Improvements [%]	25%	50%	100%
Intervention costs [US$]	$94,678,729.78	$189,357,459.56	$378,714,919.12
Power increment [%]	3%	6%	9%
Firm Energy [MW]	655.67	674.77	693.87
Firm energy increment [MWh]	19.1	38.19	57.29
Capital Recovery Factor [%]	8.58%	8.58%	8.58%
Project associated costs [US$]	$8,451,767.11	$16,903,534.23	$33,479,045.44
Cost-Benefit Ratio [US$/MW/h]	$50.52	$50.52	$66.71

Source: The authors.

The values were converted from real to US dollar, according to the exchange rate in October 2019 (date of this reference document), which was R$4.08 to each dollar. For this case study, a 25% improvement need, and 3% energy increment were established for rehabilitation; 50% of improvement need and 6% of energy increment for repowering, and finally 100% of improvement need and 9% of energy increment for modernization.

In the following mathematical development, it is shown how the values of the Capital Recovery Factor (CRF), the Costs associated with the project (TC) and the Cost Benefit Ratio (CBR) were obtained, according to eqs. 5, 6 and 7, respectively.

$$CRF = \frac{j_a * (1 + j_a)^z}{(1 + j_a)^z - 1} = \frac{0.08 * (1 + 0.08)^{35}}{(1 + 0.08)^{35} - 1} = 0{,}0858 \quad (5)$$

$$CT = (C * CRF) + (COM * \Delta_t * \Delta E_f)\ [\$]$$

$$CT = (94.678.729{,}78 * 0.0858) + (1.96 * 8760 * 19.1)[\$] \quad (6)$$

$$CT = 8{,}451{,}767.11\ [\$]$$

$$CBR = \frac{CT}{\Delta_t * \Delta E_f} = \frac{8{,}451{,}767.11}{8760 * 19.1} = 50.52 \left[\frac{\$}{MWh}\right] \quad (7)$$

Rehabilitation and repowering have recorded lower costs when compared to modernization in the cost benefit ratio analyses. There is a comparison among interventions regarding power increase to better visualize the cost-benefit index behavior (Fig. 3).

As there is an increase in power, the costs per unit of increase tend to decrease, then, there is a dilution on the value of the initial investment, which allows a scale gain; however, there is a limit to this increase. The best result is to have some higher power increase at lower cost. Here, the methodology can help with graph to choose the best one among the options.

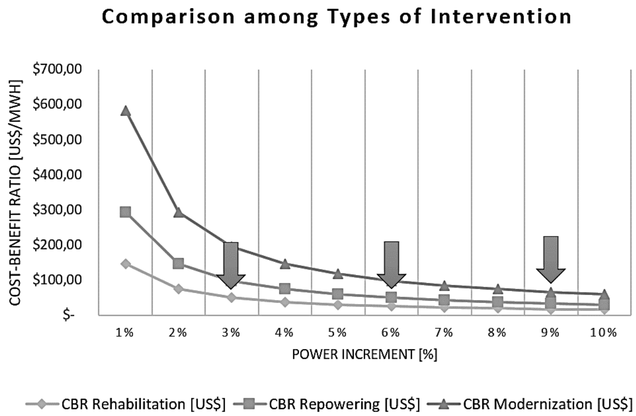

Figure 3. Comparison among the types of intervention.
Source: The authors.

There is also an increase in power when comparing the current power of a hydroelectric enterprise with its future scenario, which presents equipment upgrades and extension of useful life. This increase tends to be greater in repowering, when compared to rehabilitation. In modernization, there is even a greater gain due to the technological upgrade of the equipment, but there is also a higher cost.

When there is a 6% increase in repowering, the unit value of the power increase is equal to a 3% increase in rehabilitation. In this situation, the decision between rehabilitation and repowering is determined by (*i*) the concession content of the contract or to its renewal agreement; (*ii*) amount of annual revenue from generation; and (*iii*) the available supply for major repairs.

In modernization, the power increase can be as high as 9%, but at a higher cost in unit power increase than in other interventions.

5 Results and discussion

As the equipment wears out over time, efficiency decreases, and so do water resources in energy production. On the other hand, the benefits of rehabilitating hydroelectric plants reduce the marginal cost of operation. This finding has motivated many studies on this subject and some of them are presented in the "Literature Review" section.

While methodology application has been important to develop the rehabilitation studies of an enterprise, other approaches should take part of this discussion. For example, Adhikary and Kundu [9] reported that different factors and policies can harm the progress of a rehabilitation project. But, due to the focus of this study involving only technical aspects, no policy issues were analyzed.

According to Agugliaro *et al* [10] research, the energy segment is very well priced. Although the current electromechanical equipment and hydraulic turbines were old, there are still factors such as production cost, low maintenance and high durability that can be improved.

So, in order to make easier some technical and economic feasibility studies of a hydroelectric project, authors such as Mishra, Singal and Khatod [11] developed a correlation among equipment costs and project parameters. This study is important because it also makes easy the evaluation of hydropower plant rehabilitation projects.

Ogayar, Viddal and Hernandes [12] applied a methodology that predicted a comparison among hydropower plants that are looking for some rehabilitation, in which the index that associates cost per kilowatt is the most important variable in such choice. For Rahi and Kumar [13], the Net Present Value (NPV) method and hydrological background are the determining variables to be chosen among the options to repower a hydroelectric plant. According to Haguma, Leconte and Krau [14], who also used NPV to choose among the plant repowering scenarios, this method presents the best results.

The methodology carried out in this paper was developed to be a tool to compare different categories of intervention in a hydropower plant that needs to be repaired. So, regarding the applied methods in literature, NPV is used preferentially where there is a comparison of investments among several generating hydroelectric units. The methodologies are equally effective, so resource manager should apply them correctly.

NPV is the present value of future payments, with the deduction of both initial investment and interest rate. It also represents the cash flow in the period over an enterprise lifetime. And when positive, NPV suggests that the investment is feasible.

Net present value:
$$NPV = -FC_0 + \sum_{t=1}^{n} \frac{FC_t}{(1+j_a)^t} \quad (9)$$

Where: FC_0: Value of the initial investment [$]; FC_t: Value of cash flow in the period [$]; *t*: Year [year]; and n: Time [year].

After solving NPV equation, where the annual interest rate (j_a) is replaced by the unknown variable IRR (Internal Rate of Return) and NPV is set to zero, the rate of return on the investment is obtained. So, to have a feasible investment, IRR must be greater than the Minimum Rate of Attractiveness (MRA).

IRR:
$$-FC_0 + \sum_{t=1}^{n} \frac{FC_t}{(1+IRR)^t} = 0 \quad (10)$$

Therefore, the total value percentage of an enterprise comes out as a restrain of the methodology applied in this paper, which in the "Improvement Need" field should be carefully assigned. The "Power Increment" field must also be carefully analyzed, because there is a restrain to this increment for each category of intervention.

6 Conclusions

The first hydroelectric power plant in Brazil began its operation in 1889, which was the republic proclamation year. Currently, the Brazilian hydroelectric park has about 1,400 hydraulic generating units, many of them were about to be rehabilitated or decommissioned due to their useful lives. The structure of these projects, when deactivated, is difficult to be demolished. So, they are abandoned, while the dam will probably continue to fulfill its water retention function, otherwise, it could cause an unattended environmental impact. Thus, the following sustainable practices should be promoted to mitigate environmental problems and avoid the waste of resources: (*i*) reduce; (*ii*) reuse; and (*iii*) recycle.

Thus, this paper proposed a methodology as a tool for the decision maker, where alternatives of intervention in a hydroelectric project are analyzed, and according to the results of the analysis, a choice is made.

For the case study, according to the comparison among the different kinds of interventions, seen in Fig. 3, and the economic evaluation shown in Table 3, the rehabilitation of *Marimbondo* HPP is the most economical alternative. The 3%-increment in relation to the firm energy produced corresponds to 19.1 MW/h, with a total cost associated with the project of US$ 8,451,767.11, a value obtained using eq. 6.

Among the alternatives to intervene in an enterprise, shown in the case study, rehabilitation is the one that has proven to be technically, economically, and socially feasible.

Rehabilitation is undoubtedly one of the best and most economical ways to increase generation capacity in a short period, without significant environmental impacts. Finally, in this paper, a methodology of revitalization was presented to show its validity using a case study.

Acknowledgement

Marimbondo HPP was randomly chosen to compose the case study and an example for this proposed methodology, consequently, there is no connection among the authors and Furnas Centrais Elétricas S.A. enterprise.

Referencies

[1] Hyposo. Tecnologías de pequeña energía hidroeléctrica - Innovaciones europeas de vanguardia. Hydropower Solutions, [en línea]. Munich, 2020. [consultado: febrero 14 de 2022]. Disponible en: https://www.hyposo.eu/HYPOSO_Publications/HYPOSO_Handbook_Spanish_final.pdf.

[2] EPE. Empresa de Pesquisa Energética. Nota Técnica nº EPE-DEE-088/2019: Expansão da Geração - Repotenciação e Modernização de Usinas Hidrelétricas. Rio de Janeiro, 2019.

[3] Caselato, D., Modernização e reabilitação de usinas hidrelétricas. 1a ed. Cotia: Editora Cajuína, Brasil, 2019.

[4] Canales, F.A., Beluco, A. e Mendes, C.A.B., Usinas hidrelétricas reversíveis no Brasil e no mundo: aplicação e perspectivas. Revista Eletrônica em Gestão, Educação e Tecnologia Ambiental Santa Maria, 19(2), pp. 1230-1249, 2015.

[5] IHA. International Hydropower Report. Hydropower status report [online]. 2021. [consulted, february 14th of 2022]. Available at: https://www.hydropower.org/status-report.

[6] Pagani, R.N., Kovaleski, J.L. e Resende, L.M.M., Avanços na composição da Methodi Ordinatio para revisão sistemática de literatura. Ciência da Informação, 46(2), art. 1886, 2017. DOI: https://doi.org/10.18225/ci.inf.v47i1.1886.

[7] Ensslin, L. et al., ProKnow-C, knowledge development process-constructivist. Processo técnico com patente de registro pendente junto ao INPI. Brasil, 2010.

[8] Marafon, A.D. et al., Revisão sistêmica da literatura sobre avaliação de desempenho na gestão de P&D. Revista Gestão Industrial, 8(3), art. 001, 2012. DOI: https://doi.org/10.3895/S1808-04482012000300001

[9] Adhikary, P. and Kundu, S., Renovation modernization uprating & life extension: optimal solution for small hydropower development. International Journal of Engineering Science & Advanced Technology, 4(3), pp. 300-306, 2014.

[10] Manzano-Agugliaro, F. et al. An overview of research and energy evolution for small hydropower in Europe. Renewable and Sustainable Energy Reviews, 75, pp. 476-489, 2017. DOI: https://doi.org/10.1016/j.rser.2016.11.013

[11] Mishra, S., Singal, S.K. and Khatod, D.K., Cost analysis for electromechanical equipment in small hydropower projects. International Journal of Green Energy, 10(8), pp. 835-847, 2013. DOI: https://doi.org/10.1080/15435075.2012.727367

[12] Ogayar, B., Viddal, P.G. and Hernandez, J.C., Analysis of the cost for the refurbishment of small hydropower plants. Renewable Energy, 34(11), pp. 2501-2509, 2009. DOI: https://doi.org/10.1016/j.renene.2009.03.027

[13] Rahi, O.P. and Kumar, A., Economic analysis for refubishment and uprating of hydro power plants. Renewable Energy, 86, pp. 1197-1204, 2016. DOI: https://doi.org/10.1016/j.renene.2015.09.044

[14] Haguma, D., Leconte, R. and Krau, S., Hydropower plant adaptation strategies for climate change impacts on hydrological regime. Canadian Journal of Civil Engineering. 44(11), pp. 962-970, 2017. DOI: https://doi.org/10.1139/cjce-2017-0141

[15] Veiga, J.R.C. e Bermann, C., Repotenciação de usinas hidrelétricas: uma avaliação a partir de três estudos de caso. Revista Brasileira de Energia. 1(8), pp. 835-847, 2002.

[16] Machado, O., Informe à Imprensa: Repotenciação de usinas hidrelétricas. Empresa de Pesquisa Energética – EPE. [online]. 2008. [consulted, february 14th of 2022]. Available at: http://philip.inpa.gov.br/publ_livres/Dossie/Mad/Outros%20documentos/Informe-estudoEPE_repotenciacao_dez2008.pdf.

[17] Roussille, A.V. et al., Estudo da Reabilitação, Modernização e Futura Repotenciação dos Geradores #1 e #2 da UHE Ilha Solteira. In: VI Congresso Nacional de Engenharia Mecânica, Campina Grande, Brasil, 2010.

[18] Macedo, R.V. e Camargo, A.C., Reforma e modernização das unidades geradoras 3 e 4 da UHE Cachoeira Dourada: dificuldades e sucessos. In: XXI Seminário Nacional de Produção e Transmissão de Energia Elétrica, Florianópolis - SC, Brasil, 2011.

[19] Pessôa, S., 1 vídeo (6m22s). Cachoeiras do Marimbondo. [online]. 2012. [Consulted, February 14th of 2022]. Available at: https://www.youtube.com/watch?v=YKHEdAxJH-Q&ab_channel=SELMAPESS%C3%94A.

[20] EPE. Empresa de Pesquisa Energética. Relatório. Revisão ordinária de garantia física de energia das usinas hidrelétricas - UHEs Despachadas Centralizadamente no Sistema Interligado Nacional - SIN. Brasília, Brasil, 2017.

[21] Ferreira, M.C.O. et al., A Importância da terceirização em usina hidrelétrica: estudo de caso sobre a gestão da manutenção. In: Congresso Internacional de Administração, Bolívia, 2018.

[22] CCEE, Regras de Comercialização - Mecanismo de Realocação de Energia. [online]. 2018. [consulted, february 14th of 2022]. Available at: https://www.ccee.org.br/ccee/documentos/CCEE_076159.

[23] EPE. Empresa de Pesquisa Energética. Nota Técnica nº EPE-DEE-088/2019: Expansão da Geração - Repotenciação e Modernização de Usinas Hidrelétricas - Caderno de Apêndices. [online]. Rio de Janeiro, Brasil. 2019. [consulted, february 14th of 2022]. Available at: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-432/EPE-DEE-088_2019_Repotenciação de Usinas Hidrelétricas - Caderno de Apêndices.pdf.

M.A. de Araujo, is BSc. Eng in Energy Engineering. MSc. student at the Programa de Pós-Graduação Interdisciplinar em Energia e Sustentabilidade at the Universidade Federal da Integração Latino-Americana, Foz do Iguaçu, Paraná, Brazil.
ORCID: 0000-0002-2267-9005

J.J.G. Ledesma, is PhD in Electrical Engineering. Professor at the Programa de Pós-Graduação Interdisciplinar em Energia e Sustentabilidade at the Universidade Federal da Integração Latino-Americana, Foz do Iguaçu, Paraná, Brazil.
ORCID: 0000-0002-5979-4955

O.H. Ando Júnior, is PhD in Mining, Metallurgical and Materials Engineering. Professor at the Programa de Pós-Graduação Interdisciplinar em Energia e Sustentabilidade at the Universidade Federal da Integração Latino-Americana, Foz do Iguaçu, Paraná, Brazil.
ORCID: 0000-0002-6951-0063