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AMERICAN JOURNAL OF HYDROPOWER, WATER AND ENVIRONMENT SYSTEMS

Editorial

Demand for electricity is increasing rapidly in Latin America. Expanding and enhancing the current power generation infrastructure is thus a major concern for the region. In that context, renewable energy is bound to play a relevant role in the coming years and hydroelectric energy especially so in view of its relatively unexploited potential, which is estimated in around 690,000 MW in the region.

Our mission is to contribute to the regional integration by means of the production of knowledge in the field of hydroelectric power generation and hydromechanical systems, with focus on technological advance and the rise of quality standards, but with an eye on the priorities of a region where, well into the XXI century, millions of people find themselves deprived of electricity. That includes the topics such as the evaluation of the development of projects of low environmental impact, the role of hydroelectric powerplants in the face of the diversification of the energy matrix as well as mini- and small-hydro projects to meet the demand of areas with no access to the electrical network.

Three symposia have been held and six editions of this Journal have been published since the creation of this, the Latin Group, in 2012. Added to that are postgraduate courses and exchange programs that are being organized at present. Mexico, Brazil, Ecuador, Colombia, Uruguay and Argentina are the most active members of the Group and it is our goal to get more involved in the future.

We firmly believe in the ability of our universities to conduct the research in the field of hydraulic turbomachinery and that this knowledge will have a beneficial impact on the policy making of our countries, whether on matters related to existing infrastructure as well as the development of long-term projects and strategies.

We understand that keeping and strengthening the link between the nations currently participating is a major challenge in the framework of a constantly evolving reality, seen reflected in the availability of economic resources, the technological tools and the swings of institutional management. May this new edition of the Journal serve as evidence that, however difficult, such challenge is achievable.

Eng. Sergio O. Liscia
Presidente Latin Group 2017-2021

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All papers must be submitted in English. In case the author wants to translate the article through the journal all costs for the translation will be charged on the account of the author.

1. Formatting articles

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1.1.1 Subdivision - numbered sections

Divide your article into clearly defined and numbered sections. Subsections should be numbered 1.1 (then 1.1.1, 1.1.2, ...), 1.2, etc. (the abstract is not included in section numbering). Use this numbering also for internal cross-referencing: do not just refer to 'the text'. Any subsection may be given a brief heading. Each heading should appear on its own separate line.

1.1.2 Format

All text of the manuscript must be located within a 170 mm by 252 mm rectangle of a white A4 page or within 170 mm by 240 mm for the letter format. The margins are given in Table 1. An example of the page format is given in Fig. 1

[Table 1]: Page margin for manuscripts.

Margin Position	Top	Bottom	Left	Right
Margin size (cm)	2.0	2.5	2.0	2.0

All text should be single spaced, black and in 12-point type. "Times News Roman" or a similar proportional font should be used. Total length 15 pages in Word.

The terminology given in the *IEC Technical Report for the Nomenclature of Hydraulic Machinery* is recommended.

Introduction

State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results.

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Provide sufficient details to allow the work to be reproduced. Methods already published should be indicated by a reference: only relevant modifications should be described.

Theory/calculation

A Theory section should extend, not repeat, the background to the article already dealt with in the Introduction and lay the foundation for further work. In contrast, a Calculation section represents a practical development from a theoretical basis.

Results

Results should be clear and concise.

Discussion

This should explore the significance of the results of the work, not repeat them. A combined Results and Discussion section is often appropriate. Avoid extensive citations and discussion of published literature.

Conclusions

The main conclusions of the study may be presented in a short Conclusions section, which may stand alone or form a subsection of a Discussion or Results and Discussion section.

References

Within the text, references should be cited in numerical order according to their order of appearance. The numbered reference citation within text should be enclosed in brackets.

After the second edition all papers must have at least one reference of the American Journal of Hydropower, Water and Environment Systems.

Example: It was shown by Prusa [1] that the width of the plume decreases under these conditions.

In the case of two citations, the numbers should be separated by a comma [1,2]. In the case of more than two references, the numbers should be separated by a dash [5-7].

List of References. References to original sources for cited material should be listed together at the end of the paper; footnotes should not be used for this purpose. References should be arranged in numerical order according to the sequence of citations within the text. Each reference should include the last name of each author followed by his initials.

(1) Reference to journal articles and papers in serial publications should include:

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Sample References

- [1] Ning, X., and Lovell, M. R., 2002, "On the Sliding Friction Characteristics of Unidirectional Continuous FRP Composites," *ASME J. Tribol.*, 124(1), pp. 5-13.
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- [9] Smith, R., 2002, "Conformal Lubricated Contact of Cylindrical Surfaces Involved in a Non-Steady Motion," Ph.D. thesis, <http://www.cas.phys.unm.edu/rsmith/homepage.html>

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Abstract

A concise and factual abstract is required. The abstract should state briefly the purpose of the research, the principal results and major conclusions. An abstract is often presented separately from the article, so it must be able to stand alone. For this reason, References should be avoided, but if essential, then cite the author(s) and year(s). Also, non-standard or uncommon abbreviations should be avoided, but if essential they must be defined at their first mention in the abstract itself.

Keywords

Immediately after the abstract, provide a maximum of 6 keywords, using American spelling and avoiding general and plural terms and multiple concepts (avoid, for example, 'and',

'of'). Be sparing with abbreviations: only abbreviations firmly established in the field may be eligible. These keywords will be used for indexing purposes.

Abbreviations

Define abbreviations that are not standard in this field in a footnote to be placed on the first page of the article. Such abbreviations that are unavoidable in the abstract must be defined at their first mention there, as well as in the footnote. Ensure consistency of abbreviations throughout the article.

Acknowledgements

Collate acknowledgements in a separate section at the end of the article before the references and do not, therefore, include them on the title page, as a footnote to the title or otherwise. List here those individuals who provided help during the research (e.g., providing language help, writing assistance or proof reading the article, etc.).

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Present simple formulae in the line of normal text where possible and use the solidus (/) instead of a horizontal line for small fractional terms, e.g., X/Y. In principle, variables are to be presented in italics. Powers of e are often more conveniently denoted by exp. Number consecutively any equations that have to be displayed separately from the text (if referred to explicitly in the text).

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TECHNICAL AND ECONOMIC EVALUATIONS FOR DECISION-MAKING ON THE REPOWERING OF SMALL HYDROPOWER PLANTS AND THE OPTIMUM EXPLOIT OF EXISTING PLANTS IN BRAZIL

¹Oliveira, Marcos André

ABSTRACT

In Brazil, the Law no. 9,074 presents, in its Article 5, the concept of "optimum exploit ", which is all potential defined in its overall design by the best dam axis, general physical arrangement, levels water, reservoir and power, which is part of the chosen alternative for the division of head in a watershed.

The careful estimation of the repowering potential for the increase of installed power in Brazil depends on an individualized analysis of the existing projects, identifying the technical restrictions and the best modality of intervention with their respective extension. However in Brazil, repowering is in a process of structuring in its technical, economic and regulatory aspects.

Therefore this paper presents a proposal for the systematization of the Technical and Economic Evaluations for decision making regarding the feasibility of the repowering of Small Hydroelectric Power Plants - SHPs. This paper also presents a case study about the repowering of Lajeado SHP, built in 1971 in Brazil (installed capacity of 1.8 MW).

The results indicated that the average cost of investment for repowering is well below the average cost of investment for the construction of new SHP in Brazil.

KEYWORDS: Repowering, small hydropower plant, optimal exploit.

1. INTRODUCTION

The production of electricity in Brazil is basically from hydroelectric plants and currently these plants correspond to approximately 61.38%² of installed capacity in the country, or approximately 98,736 MW with a total of 1,264 plants.

The Southeast, South and Northeastern regions make up more than 73% of the installed hydroelectric power in Brazil and according to the EPE [1] consumed approximately 88%³ of the electricity generated in the country in 2006, practically sustaining the National Interconnected System.

Much of the Brazilian hydroelectric potential to be exploited is concentrated in the North and Central-West regions. The biggest challenge is in the fact that 70% of this potential is located in biomes of great environmental value, those of the Amazon and Cerrado, which together cover 2/3 of the national territory.

Although the hydroelectric potential to be exploited in the country is significant, the restrictions for the expansion of large hydroelectric plants are several:

- In the North and Central-West regions the relief is not favorable (plains) and there is a need to flood large areas to the reservoir, with a combination of low head and large flows. Furthermore, the geographical limitations imposed by the indigenous reserves and the environmental preservation and conservation areas are added;
- The potential reduction in the availability of water resources for the generation of energy in front of the other modalities of demand due to the guarantee of the multiple use of water.
- The need to make possible the transition of the national energy matrix based on hydroelectricity to a matrix based on integration with other sources of renewable energy.
- The need for expansion of the electric power transmission system for the North and Central-West regions.

In the short and medium term repowering is an alternative to ensure the best use of the hydraulic potential in existing plants with energy, economic and socioenvironmental gains. In the long term repowering will be the starting point for facing the aging of the Brazilian hydroelectric park [2]. In other words, repowering is one of the indispensable tools for the sustainable use of water resources for electricity generation in Brazil.

In Brazil, approximately 56%⁴ of installed capacity at the end of 2017 was already in operation before 1997. According to Bermann et al. [3] are considered old plants that have more than 20 years of operation and whose generators exceed 120 thousand hours of operation, requiring major maintenance.

In addition to the optimal exploit of the hydraulic potential in existing plants, which guarantees the rational and efficient use of water resources, among the main advantages of the repowering of SHPs can be highlighted:

- Environmental costs are minimal or nonexistent;
- There is the possibility of compensation in carbon credits;
- Lower cost compared to new plant construction;
- Possibility of implantation in the short term;
- Potential availability of additional energy close to major consumer centers (reduction of energy transmission losses).

Enabling the repowering of existing hydroelectric plants is to increase the generation of electric energy in places where socioenvironmental impacts have already been consolidated in substitution for the construction of new hydroelectric plants that also have higher costs and deadlines for implementation. Repowering contributes to the preservation and conservation of the environment in Brazil, mainly to maintain the qualitative availability of water resources [4].

The careful estimation of the repowering potential for the increase of installed power in Brazil depends on an

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²Source: Generation Information Bank of the Brazilian Electric Energy Agency - ANEEL on July 14, 2017.

³Referring to data from the last 12 months ending June 2006

⁴Source: Generation Information Bank of the Brazilian Electric Energy Agency - ANEEL on December 18, 2017.

individualized analysis of the existing projects identifying the technical restrictions and the best modality of intervention.

In Brazil repowering is in a process of structuring in its technical, economic and regulatory aspects. Since there is still no specific regulation capable of fully recognizing the gains made possible by repowering, that is, with the purpose of adequately reimbursing generation companies.

The objectives of this article are: (i) Present a proposal for systematization of the technical and economic evaluations made for decision making regarding the feasibility of the repowering of Small Hydroelectric Power Plants; (ii) To present the case study of the repowering of Lajeado SHP, built in 1971, located in the northern region of Brazil, in the state of Tocantins.

2. MATERIALS AND METHODS

2.1. Power generated in a hydroelectric plant

In a hydroelectric plant the process of energy conversion happens in stages with its corresponding amounts of energy lost during the process.

Defined the basic parameters for design, design flow and gross head, one can define the installed power and the energy generated by a hydroelectric plant.

The gross power of a hydroelectric plant is governed by the gross hydraulic potential of the point chosen for its installation and is given by the equation

$$P_B = \gamma Q H_B \quad (1)$$

where: P_B is the gross power (W); H_B is the gross head (m), Q is the flow (m^3/s) and γ is the specific weight of water (N/m^3).

The electric power generated is given by the equation

$$P_{el} = \eta_{global} \cdot P_B \quad (2)$$

where: P_{el} is the electric power generated (W) and η_{global} is overall efficiency.

Considering the main losses in the process the overall efficiency can be determined by

$$\eta_{global} = \eta_{sa} \cdot \eta_t \cdot \eta_g \quad (3)$$

where: η_{sa} is the efficiency of the hydraulic system of water adduction (SA), η_t is the efficiency of the hydraulic turbine (TH) and η_g is the efficiency of the electric generator (GE).

Figure 1 shows a schematic model of the process of converting hydraulic energy into electric energy, where P is the useful power, P_e is the power of the shaft, P_{sa} is the power used for the auxiliary services of the plant and P_{liq} is net power (maximum active electric power available from the generating plant, defined in net terms at its point of connection).

2.2. Repowering of small hydroelectric plants

Repowering can be defined as an intervention or set of interventions in the structures, hydraulic systems and electromechanical equipment involved in the process of

energy conversion of a hydroelectric project already built, with simultaneous gain of power and efficiency, reconciled with economic and socioenvironmental benefits.

Among the indicators of the state of a SHP that allow to identify the applicability of a repowering intervention can be highlighted the age of the project, operating and maintenance costs, power generation capacity, flexibility in operation and the level of exploitation of the hydraulic potential available. Also considering current technology opportunities, government incentives and the energy market.

With regard to the generation capacity of a SHP the association of some indicators such as the reduction of the average generation of the power plant, the availability factor and the efficiencies of generating sets can show the possibility of a repowering process.

In a hydroelectric plant the repowering process can be structured in the following intervention modalities: rehabilitation (restoration of energy conversion equipment to its original behavior), revitalization (applicable in plants where there are margins of projects in their dimensioning) or expansion (structured in new constructions conserving part of the existing resulting in a rearrangement of the plant). These modalities can be integrated together, according to the original hydroelectric plant project, the extension of the desired improvement and the technical and economic viability of the interventions [2].

The minimization of the costs of the repowering interventions depends on a good Planning that must integrate the Project, the Engineering, the Supply, the Commissioning and the Tests.

2.3. Technical evaluations for repowering of small hydropower plants

Already in the first moment of the diagnosis for the studies of repowering it is of extreme importance to confront the basic technical documentation of the plant (projects, manuals, data, and history of the maintenance). This will allow the confirmation of the possible need for technical refinements with surveys, measurements, tests, and complementary studies to define the technical parameters that will guide decision making regarding the extent of interventions.

In Brazil there are cases of lack of historical technical documentation remaining from old plants.

With the results of the surveys, tests and complementary studies carried out and having a careful knowledge of the current state and the residual useful life of the components of the hydroelectric power plant it is possible to define the modality of intervention for repowering.

The following are briefly described the main surveys, tests and studies that may be required.

2.3.1. Hydrological studies

The updating of the hydrological studies is necessary due to the increase of data in the historical series of tributary flows obtained in the period of operation of the plant.

A complete hydrological study for repowering includes the survey of the hydrological and meteorological information base, the determination of physiographic and climatic characteristics, the calculation of the precipitations and flows typical of the watershed where the hydroelectric plant is located.

An important result of the hydrological studies is the definition of the flow duration curves (FDC), that shows for a particular point on a river the proportion of time during which the flow there equals or exceeds certain values. Souza et al. [5] points out that in the hydropower studies the monthly flow duration curve is used.

On the other hand flood flows allow the revaluation of the stability of the dam, the capacity of the discharge devices and other aspects related to the safety of civil structures. Which give subsidy for the technical evaluation of the possibility of gain of head by the increase of the height of the dam.

2.3.2. Topographical surveys

Topographic reassessments from surveys already in place or to be performed are important for redefining or confirming the gross head available on site and allocating new civil structures.

2.3.3. Dimensional survey in the hydraulic system of water adduction

In the water conduction system of hydroelectric plants there are several types of losses of energy by friction that are estimated by specific equations. The main results of these surveys are the definition of the equation of head loss in the system of water conduction and the dimensional revaluation of the maximum capacity of the components of this system (intake, channel, tunnel, forebay tank and penstock).

2.3.4. Surveys and tests on generator sets.

Parallel to the surveys in the system of water conduction, the tests are performed on the main electromechanical equipment of the plant (hydraulic turbine and electric generator).

The tests in the generator sets concentrate on the simultaneous measurement of the turbine flow, pressure at the turbine inlet and the electrical power generated for several turbine distributor openings, registering the respective upstream and downstream water levels. This allows determining the efficiency of each generator set.

2.3.5. Geological and geotechnical surveys

Except in very particular situations surveys and geological and geotechnical studies are applicable when repowering is in the expansion modality.

These surveys allow the characterization of foundation conditions in areas where new civil and hydraulic structures will be built and existing structures strengthened or expanded.

2.4. Economic evaluations for repowering of small hydroelectric plants

The economic analysis for repowering of a SHP is made using the same methods for the economic analysis of a new power plant.

Estimating all the costs involved for each alternative considered, the cash flow of the project is elaborated with the respective revenues and expenses to analyze the economic feasibility in the project horizon. Classically the most used methods are: Net present value – NPV, Internal rate of return – IRR, Payback; and the benefit-cost ratio.

The decision on the best alternative in economic terms for repowering is taken with the joint evaluation of these methods.

In the assessment of economic feasibility the costs of interventions, equipment and other issues that are not closely related to the repowering process should be excluded, as well as only the revenue obtained with the incremental energy coming from repowering.

In addition to the revenue from the sale of incremental energy to be generated, we can add the contribution of resources with the commercialization of carbon credits, since repowering allows the addition of clean and renewable energy to the Brazilian electric system in substitution of the generation of thermoelectric energy (burning of fossil fuels that emit greenhouse gases into the atmosphere).

[Figure 2: Schematic representation of the cash flow of a repowering project.]

Figure 2 shows in schematic form the generic cash flow of a repowering project. It is important to note that, in this case, the pre-repowering and post-repowering periods refer to the period before and after the energy increment respectively.

2.5. Stages of hierarchy of technical and economic evaluations of repowering

The applicability of the hierarchical stages of technical and economic evaluations depends on the particularities of each enterprise, the economic reality of the company and the availability of reliable technical information.

2.5.1 First Stage - Simulation of theoretical maximum gain

It consists of a first approximation (estimation) of the energy gain, considering as a simplifying hypothesis the possibility of reaching the maximum theoretical efficiency for the generator sets. This can be combined with the hypothesis of optimal utilization of the tributary flows and heads available.

The maximum theoretical efficiency corresponds to the technological level of the new equipment available in the market. Currently the value of 0.92 can be considered for the maximum theoretical efficiency of a generator set.

The available technical information is readily used for preliminary simulation as input data. This will allow the definition of the characteristics of the repowering generator set and the projection of the energetic gains. Repowering costs are also estimated at this stage.

Already in this preliminary stage are raised the technical restrictions. Mainly environmental restrictions.

If this first approximation indicates potential technical, economic and environmental feasibility for the plant's repowering, then the surveys, tests and additional specialized studies that will be necessary to subsidize the subsequent stage should be defined.

2.5.2. Second Stage - Technical, economic and environmental feasibility study

Based on the results of the surveys, tests and complementary studies carried out and having a thorough knowledge of the current state of the equipments and the residual useful life of the equipments, it is possible to define the repowering mode (rehabilitation, revitalization or expansion).

The economic variables and the merit indices obtained in the technical and economic analyzes are used to choose the best repowering alternative, of which it can be highlighted: power gain (kW), energy gain (MWh), total cost to generate additional energy (US\$/MWh), total cost to increase power (US\$/kW), cost of unavailability (US\$), net present value - NPV, Internal rate of return - IRR, time of return of investment and revenue-cost ratio.

If there are several plants that are candidates for repowering the same variables and indexes serve to choose or rank the best opportunities.

In Brazil, the variable that most influences the decision making as to the feasibility or not of a repowering project is the economic one. The environmental aspects do not constitute as restrictions that can make a repowering project unfeasible. Except in cases where there is an increase in the operational level of the reservoir (flooded area increase) or exceptional cases.

The environmental licensing of repowering follows the same guidelines of current regulations for new hydroelectric plants in Brazil.

3. RESULTS AND DISCUSSION

3.1. Location and general description of Lajeado SHP

Lajeado SHP was built in 1971 by Goiás Electric Power Plants - CELG and is currently managed by the Alvorada Energia concessionaire which was acquired by Enel Brasil in 2006.

The project is located in Lajeado city, state of Tocantins, Brazil, at coordinates 9°50'08.72"S and 48°17'37.82"W, distant approximately 57.45 km from the capital Palmas.

The Lajeado SHP is a plant of high head and starts with the derivation of the main river. It is 1.8 MW of original power, whose general arrangement is constituted by a dam with integrated spillway in the central part, intake, channel and tunnel, forebay tank, penstock, power house with a generator set. The average annual historical generation is 13,747 MWh.

The dam is of the gravity type in concrete with 9.3 m of maximum height and 90.0 m of length. The spillway is of the free overflow type (Creager profile) with 40.70 m in length and approximately 7.40 m in height.

[Figure 3: Schematic cross-section of the dam and spillway.]

According to Figure 3 there is the possibility of adding up to two wooden floodgates above the spillway to increase the head and optimize the generation of energy in the dry season.

The Lajeado SHP reservoir is formed by the derivation of the Lajeado river and has an area of 0.055 km² at the normal water level. The useful volume of the reservoir is negligible (it is not intended to regulate flow). The operating water levels are: normal maximum at 337.64 m and minimum normal at 337.44 m.

The power house is of the sheltered type and has approximately 112 m² of built area. It is in very good condition.

The electrical substation is the homeless type and occupies an area of 685 m². Composed basically of a 2,500 kVA electrical transformer with voltages of 2,400/34,500 V. It is located near the power house.

The existing electric transmission system consists of a three phase line operating at 34.5 kV, with the capacity to carry 1.9 MW with inductive power factor 0.8 at a current

of 39.7 A per phase. Being that the energy produced by the existing arrangement is transported by this line to the Barra do Lajeado electrical substation, belonging to the local concessionaire.

According to standard ABNT 5422, considering an ampacity of 0.7 A/mm², for the cross section of the existing cable of 57 mm², cable 1/0, the transmission system is already at its maximum limit. Therefore it is necessary to build a new interconnection line in the expansion of the existing SHP [6].

3.2. Technical evaluations for repowering of Lajeado SHP

3.2.1. Hydrological studies

The watershed of the PCH Lajeado has a drainage area of 514 km². Since its physiographic characteristics indicate that it is a watershed that is less subject to floods and that has a relatively irregular and elongated form.

A historical series of flow with 33 years of data was obtained through the transposition of flows of fluviometric stations available in the region.

Through the hydrological analysis of the fluviometric stations shown in Table 1 it concluded that the hydrological behavior of the watershed of the Porto Alegre station and of the watershed under study is approximately similar, with a correlation coefficient of 0.78. The flow series for Lajeado SHP was obtained through a transposition relation considering the respective drainage areas.

Hydrological studies were completed in early 2008.

From this point was obtained the duration curve of the average monthly flows (Figure 4).

[Figure 4: Duration curve of the average monthly flows in the Lajeado SHP.]

It should be noted that the number of hydrometric stations in the northern region of Brazil is still insufficient. Therefore flow regionalization methods are used.

The ecological flow in the state of Tocantins corresponds to 25% of the flow with 90% of duration in the flow duration curve.

For the definition of flood flows the series of maximum flows were adjusted to the theoretical distribution of probabilities, Type I Extremes (Gumbel) and Log-Pearson III, with extrapolation for different recurrence times. The best fit was the Log-Pearson III distribution.

The review of the hydrological studies showed an under - sizing of the plant in comparison to the natural flows of the river. Table 2 summarizes the results of hydrological studies.

[Table 1]: Fluviometric stations analyzed.

Station name	Brazilian code	Area Drainage (km ²)	Coordinates		Data time range
			Longitude (degrees)	Latitude (degrees)	
Muricilândia	28150000	1.600	-48.6197	-7.1544	1974 - 2006
Arapoema	27550000	1.386	-49.0453	-7.6136	1988 - 2006
Fazenda Craveiro	27370000	295	-48.9708	-9.6036	2000 - 2007
Ponte Rio Dueré	26790000	1.442	-49.2667	-11.3167	2000 - 2007
Porto Alegre	22190000	1.930	-47.0453	-11.6108	1975 - 2006
Dois Irmãos	22850000	9.543	-47.8133	-9.3114	1973 - 2007
Itacajá	23150000	2.776	-47.7653	-8.3917	1973 - 2007
Jatobá	22680000	13.855	-47.4725	-9.9953	1973 - 2007
Bernardo Syão	27530000	1.541	-48.8789	-7.8789	2000 - 2007
Jacaré	23230000	5.069	-47.2611	-7.9633	1984 - 2007

3.2.2. Topographical surveys

A topographic survey was carried out in the area of interest by a specialized company. The gross head for the current arrangement was then confirmed to be 92 m.

It is important to note that there was no change in the water level of the reservoir (337.64 m) in the repowering studies. However the downstream water level was reallocated to a point with no significant slopes in order to enable head gains. The downstream water level reached the elevation 230.55 m. This resulted in a gross head of 107.09 m.

[Table 2]: Summary of the characteristic flows for Lajeado SHP.

Average long term flow	9.97 m ³ /s
Flow duration of 50% (median)	5.07 m ³ /s
Flow duration of 90%	1.70 m ³ /s
Flow duration of 95% (Steady flow)	1.60 m ³ /s
Ecological flow	0.425 m ³ /s
Flood discharge (recurrence time 100 years)	209.1 m ³ /s
Flood discharge (recurrence time 1,000 years)	281.1 m ³ /s

3.2.3. Surveys in the hydraulic system of adduction

The hydraulic system of adduction of the plant is composed of: intake (right side reservoir), channel (concrete), tunnel (concrete), forebay tank and penstock.

The evaluation of the hydraulic system of adduction was carried out through geometric measurements and corresponding dimensional analysis of all its components, as well as surveys the hydraulic losses from measured values of turbinated flow under load conditions of 25%, 50%, 75% and 100%.

Among the main results are: the adduction channel of rectangular section extends for 125 m and the calculations indicated that it supports a maximum flow of 4.59 m³/s; the forebay tank has a useful volume of 114.84 m³; the penstock is 320 m long and has a maximum adduct capacity of 6.78 m³/s.

3.2.4. Surveys and tests on generator sets

The Lajeado SHP generator set consists of a simple horizontal Francis turbine and synchronous electric generator. The tests carried out at the end of 2007 had as main objective to reveal the performance of the main equipment of the plant.

In parallel to the measurement of turbine flow under load conditions of 25%, 50%, 75% and 100%, electrical quantities and hydraulic quantities (flow, heads, pressure and losses in the adduct) were measured. The overall efficiency of the generator set was then obtained (Figure 5).

The maximum power generated by the plant is 1,990 kW with the fully open hydraulic turbine distributor. However due to the high levels of audible noise resulting from excessive cavitation it was concluded that the operation of the plant should be limited to a maximum power of 1,770 kW.

In order to determine the efficiency of the electric generator, its electrical losses were determined by the calorimetric method, according to IEEE-115 and ABNT NBR-5452 standards. Defining the losses in the electric generator for the load conditions of 25%, 50%, 75% and 100% was obtained the efficiency of the same. Figure 6 shows the efficiency of the electric generator.

In addition the the capability diagram of the electric generator was obtained with the parameters obtained in these surveys.

Although the current generators present a much higher efficiency, it is concluded that the generator of the Lajeado SHP, is in a range of satisfactory performance. Its efficiency reached a maximum value of 96.2%.

The results obtained for the performance of the hydraulic turbine are shown in Figure 7 for the same load conditions. The efficiency of the turbine is low and the maximum value was 83.9%. Currently the hydraulic turbines can achieve an efficiency of approximately 93%.

3.3. Economic evaluations and Hierarchical stages of the technical and economic evaluations of repowering of Lajeado SHP

3.3.1 First Stage - Simulation of theoretical maximum gain

Due to the transitions of owners since the construction of the plant much of the historical technical documentation has been lost, leaving only basic technical information and scarce remnants of the projects. Thus, it was not possible to simulate the theoretical maximum gain.

However, knowing the underutilization of the available flows and the existence of a high gross head (atypical head for the North region of Brazil) the complementary studies to be realized to know the technical characteristics of the plant were defined.

The underutilization of the local hydraulic potential was verified by the observation of significant discharge of water by the spillway in some months of the year combined with the possibility of head gain.

3.3.2. Second Stage - Technical, economic and environmental feasibility study

Considering the technical information raised four possibilities of repowering in the expansion modality for the Lajeado SHP were established.

[Figure 8: Alternatives for repowering.]

The alternatives considered (Figure 8) are briefly described below:

- Alternative I: It is based on the use of part of the existing water intake system through a bypass in the penstock near the present power house to bring water to a new power house located downstream (near the existing bridge) resulting in a gross head of 97.45 m;

- Alternative II: It is based on the use of existing dam, but discarding the entire current adduction system. A new adduction system (parallel to existing one) was then built for a new power house located downstream of the current one (below the existing bridge) totaling a gross head of 107.09 m;
- Alternative III: It is based on the use of the existing dam and construction of a new adduction system, however with an alternative route to the first two (Alternatives I and II) totaling a gross head of 107.36 m;
- Alternative IV: It is similar to Alternative II but considers a power house built between the current power house and the bridge located downstream providing a downstream water level of 234.47 m and a gross head of 101.98 m. This corresponds to a reduction of 5.11 m in relation to the gross head contemplated in Alternative II.

Then an incremental simulation was performed to expand the plant for each of the alternatives contemplated through pre-sizing and respective quantification of the costs involved. Following the energy benefits were converted into economic terms and thus could be generated the economic reference indicators: time of return of capital, net present value and internal rate of return.

3.3.2.1. Alternative I

Knowing that the restriction point in the water adduction system (complementary studies) is the channel whose maximum adduction capacity is 4.59 m³/s the plant's expansion costs were reached up to this limit. For this costs were calculated considering a unit increment of flow according to Table 3.

[Table 3]: Costs of Alternative I.

Flow (m ³ /s)	2.00	3.00	4.00	5.00
Power (kW)	1,746.95	2,620.42	3,493.89	4,367.36
Low pressure system (US\$)	-	-	-	-
High pressure system (US\$)	303,800.41	362,215.00	552,223.61	605,529.30
Power house (US\$)	1,475,000.00	2,145,280.00	2,784,000.00	3,360,000.00
Other costs (US\$)	599,072.01	809,341.27	1,123,508.56	1,314,412.60
Total cost (106 US\$)	2.378	3.317	4.460	5.280
Cost/power (US\$/kW)	1,361.16	1,265.77	1,276.44	1,208.95

The incremental economic simulation revealed the best option as the installation of a power house downstream from the current power house, using all the available adduction system (4.59 m³/s), totaling 4 MW of installed capacity.

3.3.2.2. Alternative II

The turbine's flow was sought to maximize the economic benefits since there were no operational restrictions. The plant expansion costs were estimated for a turbine flow rate of up to 20 m³/s. For this a flow increment of 5 m³/s was considered according to Table 4.

The incremental economic simulation, combined with the achievement of a typical capacity factor (0.6), for the considered head, revealed the best option as a new plant with a project flow of 9.4 m³/s representing an additional power of 7.9 MW.

During 4 months of the year there will be available flow to activate also the turbine of the existing power house. The power of 9.65 MW will be available for 3.5 months per year.

[Table 4]: Costs of Alternative II.

Flow (m ³ /s)	5.00	10.00	15.00	20.00
Power (kW)	4,367.40	8,734.79	13,102.19	17,469.59
Low pressure system (US\$)	66,165.50	97,042.50	142,731.88	168,356.00
High pressure system (US\$)	1,568,859.86	2,870,765.28	3,886,570.41	5,422,106.48
Power house (US\$)	3,360,000.00	5,835,000.00	8,228,000.00	10,575,000.00
Other costs (US\$)	1,577,424.34	2,670,747.80	3,794,340.32	4,853,045.06
Total cost (106 US\$)	6.572	11.474	16.052	21.019
Cost/power (US\$/kW)	1,504.89	1,313.55	1,225.11	1,203.15

3.3.2.3. Alternative III

In this alternative it was also considered a flow increase of 5 m³/s up to the limit of 20 m³/s for plant expansion (Table 5).

The incremental economic simulation combined with the achievement of a typical capacity factor (0.6) for the considered head revealed the best option as a new plant with a project flow of 9.4 m³/s representing an additional power of 7.9 MW.

[Table 5]: Costs of Alternative III.

Flow (m ³ /s)	5.00	10.00	15.00	20.00
Power (kW)	4,367.40	8,734.79	13,102.19	17,469.59
Low pressure system (US\$)	172,855.50	239,315.00	342,171.88	395,744.00
High pressure system (US\$)	1,152,216.80	2,345,002.89	2,808,360.00	3,926,432.27
House of machines (US\$)	3,360,000.00	5,835,000.00	8,228,000.00	10,575,000.00
Other costs (US\$)	1,498,238.71	2,572,775.26	3,569,835.41	4,529,028.13
Total cost (106 US\$)	6.183	10.992	14.948	19.426
Cost/power (US\$/kW)	1,415.79	1,258.43	1,140.91	1,112.00

3.3.2.4. Alternative IV

In this alternative it was also considered a flow increase of 5 m³/s up to the limit of 20 m³/s for plant expansion (Table 6).

Consistent with previous analyzes, the incremental economic simulation, coupled with the achievement of a typical capacity factor (0.6) for the considered head revealed the best option to be that of a new plant with project flow equal to 9.4 m³/s representing an additional power of 7.5 MW. However maintaining the existing power house.

During 4 months of the year there will be available flow to activate also the turbine of the existent power house. The power of 9.3 MW will be available for 3.5 months of the year.

[Table 6]: Costs of Alternative IV.

Flow (m ³ /s)	5.00	10.00	15.00	20.00
Power (kW)	4,148.54	8,297.07	12,445.62	16,594.16
Low pressure system (US\$)	66,165.50	97,042.50	142,731.88	168,356.00
High pressure system (US\$)	1,176,644.90	2,153,073.96	2,914,927.81	4,066,579.86

Flow (m ³ /s)	5.00	10.00	15.00	20.00
House of machines (US\$)	3,360,000.00	5,835,000.00	8,228,000.00	10,575,000.00
Other costs (US\$)	1,577,424.34	2,670,747.80	3,794,340.32	4,853,045.06
Total cost (106 US\$)	6.180	10.756	15.080	19.663
Cost/power (US\$/kW)	1,489.74	1,296.34	1,211.67	1,184.93

3.3.2.5. Definition of the best alternative for repowering

Table 7 presents the synthesis of the results that allowed the decision making regarding the best alternative of arrangement for repowering. The values practiced in the Brazilian market in January 2010 were considered for the composition of the parameters adopted for economic evaluations.

[Table 7]: Summary of economic analysis results of alternatives.

Alternative	Flow (m ³ /s)	Power (MW)	Investment (106 US\$)	Payback (anos)	NPV (106 US\$)	IRR (%)
I	4.6	4.0	4.8	4.7	13.2	55.0
II	9.4	7.9	10.6	5.5	20.9	42.4
III	9.4	7.9	10.1	5.3	21.3	44.7
IV	9.4	7.5	10.0	5.3	21.3	45.4

After integrated technical and economic analysis it can be defined that the most viable alternative is alternative IV.

At this stage the results indicated a cost of 1,328 US\$/kW for a better alternative, excluding the cost of the associated transmission system and interest.

Through a study carried out by EPE [1] a parameterized investment cost for hydroelectric plants in Brazil was reached between 800 and 1,500 US\$/kW. The research carried out by Tiago & Caetano [7] based on the cost sheet of 63 SHP projects in Brazil resulted in an average implementation cost of 1,033 US\$/kW.

Canales & Beluco [8] carried out a study to elaborate parametric cost curves for SHP in Nicaragua, based on 18 pre-feasibility studies with costs and previous experiences in this country and other countries of the Central American region, reaching the average cost of approximately 5,000 US\$/kW. The authors concluded that this value, considered high, is possibly justified by the inclusion of the cost of transmission lines and the geographic difficulties inherent in rural electrification.

3.3.2.6. Optimization of installed power and determine the new generator sets of the expanded part

Selecting the best alternative for plant repowering, power plant refinement was achieved through an optimization process that sought to maximize the utilization of available hydraulic potential (maximization of energy and economic benefits).

Starting from the updated monthly flow duration curve, the corresponding energy curve for the use was obtained (Figure 9).

As already presented in this paper the new gross head resulting from the technical evaluations is 107.09 m in contrast the original gross decrease of 92 m.

The conception of repowering (modality expansion) of the Lajeado SHP considers the use of the existing hydraulic system and power house, including generator set installed whose nominal turbine flow is 2.6 m³/s. Therefore the new installation will only start operating with availability of flows of more than 2.6 m³/s.

[Figure 9: Longitudinal section of the additional power house.]

This decision is justified because for the best alternative for repowering (alternative IV) a project flow of $9.4 \text{ m}^3/\text{s}$ was obtained for expansion. Because choosing to keep the additional turbines operating with equal or lower flows at $2.6 \text{ m}^3/\text{s}$ (approximately 28% of the load) would be to operate below the lower limit of the Francis turbine optimum operating range. That is, the new generator sets, even with relative efficiencies higher than the existing generator set, would operate with very low efficiency in part of the time, resulting in significant losses of power generation.

For the process of optimization of the installed power of the new power house reference values were adopted for certain quantities. The main reference values are summarized in Table 8.

The sale price of the energy generated ($80.544 \text{ US\$/MWh}$) was adopted as the average of the tariffs practiced in the free contracting market in Brazil at the beginning of 2010. From this amount the estimated costs of operation and maintenance ($4.354 \text{ US\$/MWh}$) were subtracted.

[Table 8]: Assumptions adopted.

Item	Valor
Adduction system losses	2.38 %
Nominal turbine efficiency	92 %
Minimum turbine efficiency	82 %
Efficiency of the electric generator generator	96.5 %
Scheduled unavailability	360 hours
Forced Unavailability	100 hours
Investment amortization period	30 years
Interest rate	10 % per year
Sale price of energy	$80.544 \text{ US\$/MWh}$

The result of the optimization process of the best repowering alternative of the Lajeado SHP indicated an optimum design flow of $8.8 \text{ m}^3/\text{s}$ and an installed power of 8.0 MW. What can be obtained in the curve that relates the net benefit to the installed power whose optimal point points to the maximum net present value.

The summary of the results of the technical and economic analyzes for the expand part are presented in Table 9.

[Table 9]: Results.

Item	Valor
Upstream water level	337.64 m
Downstream water level	230.55 m
Gross head	107.09 m
Net head	104.50 m
Project flow	$8.8 \text{ m}^3/\text{s}$

Item	Valor
Installed power	8 MW
Capacity Factor	0.55
Annual energy generated	36.3 GWh
Total cost of plant	$15.97 \times 106 \text{ US\$}$
Annual gross revenue	$2.07 \times 106 \text{ US\$}$
Annual net revenue	$0.38 \times 106 \text{ US\$}$
Internal rate of return	12.98 %

The study to determine the new generator sets resulted in 2 additional units (Figure 10) with a rotation of 720 rpm and a maximum suction height of 1.56 m. Each turbine has a power of 4.124 MW and flow of $4.4 \text{ m}^3/\text{s}$ for a gross head of 107.09 m and respective net head of 104.5 m. The correlated generators have a unit power of 4.440 MVA.

All of this at a final cost of $1,966 \text{ US\$/kW}$ including a new electric transmission system for plant interconnection (and interest rate).

The total estimated period for completion of the works and the start-up of the first generator set of the expand part is 24 months.

The existing generator set will remain in operation for a large part of the time during interventions, minimizing the plant downtime. This is one of the advantages of repowering in the expansion modality.

Regarding the interconnection of the power plant with the regional transmission system, the results indicated the need to implement a transmission line from the plant to the nearest power grid. This line will have a voltage of 34.5 kV and approximately 3.5 km in length.

4. CONCLUSION

The repowering of SHPs is an important tool for the rational and efficient use of water resources in Brazil.

Old SHPs usually depend on the diagnosis of their technical characteristics through surveys, tests and complementary studies to make the decision on the best alternative of repowering intervention.

Usually the repowering modality that has the highest cost is the expansion modality. However even in this modality the average cost of investment in repowering remains lower than the cost of investing in the construction of new hydroelectric plants in Brazil.

Through the case study of Lajeado SHP it was possible to confirm the applicability of the hierarchical stages of the technical and economic evaluations to define the viability of repowering.

In the economic evaluation stage of the alternatives for repowering the cost of $1,328 \text{ US\$/kW}$ was obtained for a better alternative (excluding the cost of the associated transmission system and interest rate) and an installed power of 7.5 MW. Already after the stage of optimization of the installed power to cost of $1,996 \text{ US\$/kW}$ (including associated transmission system and interest rate) was obtained and an installed power of 8 MW.

The case study also confirmed the need for prior technical analysis on the characteristics of the interconnection transmission system of the hydroelectric plant. If this system supports carrying the additional energy provided by the repowering can be characterized as a restriction that can make it unfeasible. For Lajeado SHP this cost reached 25% of the total cost.

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