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Sustainability as a perspective for the repowering of small hydroelectric plants in Brazil: estimation method

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Abstract: Repowering is a sustainable option for relatively old hydroelectric plants. However, it is still in the process of developing its technical, socio-environmental and regulatory aspects in Brazil. Moreover, there are few papers available in the literature on the subject. A gap in the area is the lack of methodologies that direct the measurement of benefits in suitable enterprises, to prioritize the most opportune ones, reduce risks, and encourage this practice nationally, regionally, and among agents. This paper presents a theoretical discussion of the practices currently employed and proposes an accessible method (simple, fast and low cost) to support decision-making regarding the applicability of repowering in small hydroelectric plants. The results show the environmental sustainability of the practice given the limitations and challenges that currently involve the construction of large hydroelectric plants.

Keywords: Sustainability, Repowering, Small Hydroelectric Power Plants, Maximum Theoretical Gain, Optimum use, Refurbishment, Uprate, Renewable resources.

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1 Introduction

It is well known that the brazilian electricity matrix is mostly dependent on the hydro source. In 2019 the country ranked first among the top ten with the largest individual increases in installed capacity (IHA, 2020). In the same year, 64.9% of the national offer was supplied by hydroelectric plants and, considering the other renewable sources, this figure rises to 83.0% (EPE, 2020).

Hydropower repowering, worldwide, has been driven by the lack of perennial energy and the slow pace of new hydropower addition programs (RAHI; CHANDEL, 2015). Moreover, there is the need to meet global efficiency, safety, and socio-environmental targets. In addition, alternative renewable electricity sources (photovoltaic, biomass, wind, tidal power and so forth), introduced as alternative or complementary options to traditional ones (VASCO et al., 2019), are more restrictive because they are intermittent (RAHI; CHANDEL, 2015).

Repowering has been reasonably reported in the literature, as a strategic and competitive option (QUARANTA et al., 2021); addressing research activities and practical experience (ROMERO-AÑAZCO et al., 2020; OLIVEIRA, 2018; AJAO et al. 2016; RAHI; CHANDEL, 2015); in the aspects for cost analysis (KISHORE et al. 2021; OLIVEIRA, 2017; OGAYAR et al., 2009); and, mainly, in the scope of adding, improving or replacing turbines and generators (SILVA et al., 2021; MAGALHAES et al., 2020; KUCHINSKAYA; NOVOZHILOV, 2011; ANEEL, 2011; GÓMEZ et al., 2008; WWF-BRASIL, 2006).

Recently, Queiroz et al. (2019) highlighted repowering as an action to mitigate the negative consequences of future climate in brazilian generation systems. Thus, considering the specificities of the brazilian electricity sector, the article reflects on what constitutes repowering as a sustainable practice and how to advance the debate from practical propositions.

Brazilian hydroelectric plants are classified by power, into Hydroelectric Power Plant - HPP (greater than 30 MW), Small Hydroelectric Plant - SHP (greater than 5 MW and equal to or less than 30 MW) or Hydroelectric Generating Plant - HGP (equal to or less than 5 MW), whose limits and conditions were recently updated by Normative Resolution No. 875 of 2020. The last two classes, smaller in size, are of particular interest to this work and have been generically named Small Hydroelectric Plant - SHP in the text.

In this scenario, SHP repowering is a timely tool. This is because the increase in energy is accompanied by minimal incremental negative environmental impacts (QUARANTA et al., 2021; GOMES, 2013; GYORI, 2007; WWF-BRASIL, 2004), the guarantee of better use of water resources, a reduced cost compared to the implementation of new hydroelectric plants, and the possibility of interconnection with other local socio-environmental interests.

The hydroelectric repowering technique is defined as an intervention or set of interventions in the structures, hydraulic systems, and electromechanical equipment involved in the energy conversion process of a built project, with a simultaneous gain of power and efficiency (OLIVEIRA, 2018, 2017).

Nationally, this technique has been considered for SHP with at least 20 years of operation. Under this criterion, 9% of SHP and 35% of HGP operating in the country in 2019 would be susceptible to this possibility. According to Oliveira (2018), around 56% of the brazilian installed capacity at the end of 2017 was already in operation before 1997. Therefore, repowering is also a solution to address the aging of the national hydroelectric park (EPE, 2021, 2019; OLIVEIRA, 2012).

Currently, as important as government encouragement for a widespread and conscious adoption of repowering as an ongoing practice for sustainability, is the adoption of a systemic approach for assessing its socio-environmental benefits. The multidimensional assessment of hydropower sustainability is a current topic of discussion (TANG et al., 2018).

Supplying the demand for electricity in the country, which will grow approximately 3.1% per year between 2019 and 2030 (EPE, 2021), is admittedly of public interest. The advantages of the implementation of a large hydroelectric plant (HPP) in Brazil are historically based on the importance of the strategic reserve in its accumulation reservoir, competitive cost, high capacity factor compared to other renewable sources, and the ability to meet peak demand. On the other hand, there are the disadvantages of the multiplicity of negative environmental impacts that are consolidated during the life cycle of this project. These two antagonistic aspects constitute historical debates and controversies in brazilian energy planning.

For a long time, economic advantages have taken precedence over other interests involved. However, with the increasing environmental constraints that are being established to protect the ecosystem and socio-cultural resilience of sites already affected or to be affected by the construction of hydroelectric projects (MORETTO et al., 2012), these disputes are intensifying.

It is known that these disputes occur mainly because of territory. According to Zhouri and Oliveira (2007) the territory is understood as property by the electricity sector, which assigns an economic valuation to it, like any other commodity. Considering different looks within geography, Vargas (2014) makes expositions of meanings attributed to territory and highlights its complexity and diversity of contents. However, he concludes that, regardless of the theoretical approach, it is possible to say that territory is concrete insofar as it is constituted by recognizable materiality of elements of nature and man-made objects, but also abstract because it refers to subjective constructions, significations, and representations that constitute symbolic referents.

Interpreted as a social process of appropriation and transformation of space, within the characteristics that allow it to be differentiated from its surroundings, the territory is a dynamic interaction of nature (physical and biotic environment) and social practices (anthropic environment). In this sense, the theory of integrated approaches for the management of multiple-use water has come to rule hydropower governance from the local to the international level (LINDSTRÖM; RUUD, 2017), promoting not only the coordinated development and management of water but of the territory and related resources (JONES et al., 2006).

The reasons that make the repowering of hydroelectric plants a sustainable option are: the dynamics of natural resources that require constant updates in the boundary conditions that govern the sizing or operation of hydroelectric plants; the change in evaluation criteria or perception of socio-environmental interactions of a project; technological advances; and the growing demand for energy. In addition to its contribution to offsetting the aging of Brazil's hydroelectric park.

Nevertheless, the realistic quantification of the increment of energy to be generated by repowering hydroelectric plants, in the regional or national domain, is tied to the individualized evaluation of these assets, or liabilities in the case of decommissioned plants (OLIVEIRA, 2018). Therefore, the present work is justified because, besides the theoretical discussion of currently employed practices and an approach to SHP repowering from the perspective of sustainability, it proposes a concrete solution to support decision-making regarding its applicability.

The main contributions of this paper are new insights into the sustainable aspects of SHP repowering and the explain of the Theoretical Maximum Gain Method - TMGM. The TMGM is composed of dimensional analyses of these plants and techniques to define the repowering modality. The Bagagem SHP, located in the state of Tocantins, was chosen to demonstrate the application of the proposed method. The choice was due to the authors' previous knowledge about the specificities of the plant and spatial proximity; the sufficient availability of data (provided by the state environmental agency); and being located in the legal Amazon, where the challenges for the expansion of the sustainable supply of electricity are maximized.

2 Challenges for the implementation and repowering of hydroelectric plants in Brazil

The implementation of new hydroelectric developments, especially large ones, is being increasingly limited, especially due to socio-environmental issues (OLIVEIRA, 2017; GOMES, 2013; GYORI, 2007; EPE, 2007), while most of the hydroelectric potential to be exploited (concentrated in the North and Midwest regions) is located in the Amazon and Cerrado biomes (OLIVEIRA; OLIVEIRA, 2021; EPE 2007), which have notoriously great environmental value for the country (MORAN, 2020). This subject is well discussed and summarized in Oliveira (2018).

Interestingly, Corà et al. (2019) summarize five challenges for hydropower projects from an environmental perspective: ecological continuity, i.e. fish migration and sediment transport; water quality; ecological flow; downstream peak flows, which can negatively affect the hydromorphological section of the river and aquatic organisms (stranding mortality, habitat modification, water quality, etc.); and the mitigation hierarchy for biodiversity.

The environmental impacts caused by the implementation of a hydroelectric dam in the physical, biotic and anthropic environments, are related mainly to its geographical location and the characteristics of its reservoir (flooded area, floodable area, useful volume, retention time, flood damping capacity, etc.). However, these impacts are perceived and pondered in different ways by the various social actors involved, and a holistic view of the subject involves integrating the technical and participatory approaches.

From the point of view of those affected by hydroelectric dams in Amazonian watersheds, Utsunomiya et al. (2020) draw attention, for example, to the challenge of a systemic assessment of environmental impacts when dealing with indigenous peoples and traditional communities, as opposed to the usual fragmentation of studies into biotic, physical, and socioeconomic environments.

On the cumulative impacts arising from hydroelectric dams, Athayde et al. (2020) ponder the shift of focus from the hydroelectric project itself to the local and regional social-ecological system affected by various actions or projects in the territory, such as other dams, climate change, demographic changes, among others, as a resilient and sustainable direction for the Brazilian Amazon. Therefore, Perius and Carregaro (2012) advocate the desirability of strengthening SHP as a renewable, environmentally less impactful, and socially more appropriate energy source.

In addition, Castilho (2017) highlights the aggravation of multiple water use conflicts, one of these uses being energy generation, if we consider the interests related to land and water by different actors and the contradictions that will demand new forms of energy production. And rightly, Castilho (2019) calls attention to the expansion of the debate and defense of the diversification of the brazilian energy matrix, with foundations in efficiency, decentralization, strengthening of local production, environmental responsibility, equity, and respect for peoples.

Advances for effective repowering of hydropower plants in Brazil have been intensified for large hydropower plants, HPP, mainly for the addition of generating sets in those that have originally empty installation sites (EPE, 2019, 2012; LEMOS, 2014). On the contrary, the full potential for SHP repowering is not yet known.

In order to know the potential to repower SHP, it is of fundamental importance to develop methodologies for identification and quantification of its benefits, as well as the creation of regulatory mechanisms for recognition and remuneration of the incremental energy made available. This corroborates the pertinence of the present report because many generating agents cannot or do not want to take risks with the repowering, which includes the expense of complementary studies and surveys for the diagnosis of the hydroelectric use, subsequent feasibility study and repowering project.

Regulatory proposals to encourage the dissemination of the repowering of SHP include the exemption of the review of hydroelectric inventories; definition of deadlines for approval and obtaining authorizations; a competition scenario for hydroelectric plants; definition regarding the extension of the concession; changes in the concession/authorization regime (BARROSO, 2009); and use of the incremental power of repowering as an Operating Power Reserve - OPR (EPE, 2019; ANEEL, 2011).

Another important point about the regulatory aspect of repowering is related to the need for simplification of environmental licensing, which generally follows the same guidelines as a new plant. But, except in cases where there is an increase in the operating level of the reservoir, that is, an increase in the flooded area, or exceptional cases, there are no environmental impediments to SHP repowering, quite the contrary, the benefits are numerous (OLIVEIRA, 2012) for the strategic and environmentally viable use of natural resources in an area already impacted.

Thus, it is imperative to stimulate the repowering of SHP, which meets the interest of the whole society in developing solutions for decentralized generation of electricity, through renewable sources, and the continued development of sustainable practices. The sustainable contributions of the careful implementation of SHP and the repowering of existing SHP, which includes deactivated ones, should be at the center of the discussion on the challenges and limitations that involve the construction of new HPP in Brazil.

3 Coverage of the benefits of repowering hydroelectric plants

The fact that hydroelectric plants are generally large and complex does not justify any neglect of the associated sustainability aspects (LIU et al., 2013). The difficulty lies in the measurement of socio-environmental issues that are still treated as externalities when conflicts and contradictions of interest are found even in topics that should be well delimited in brazilian environmental licensing.

Sustainability is a multifaceted concept as it involves the environment, economy and society (HAYASHI et al., 2014). Several definitions of sustainability and sustainable development, with some slight variations, are available in the literature (LIU et al., 2013). Sustainable development is the core concept (ZHANG, 2017), and was presented in the 1987 Brundtland Report: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987, p.15). The term sustainability is already a development of this initial concept and in essence means that what you are doing is not at the expense of future generations (LIU et al., 2013; WCED, 1987). In this way, SHP repowering has a relevant contribution, more in the sense of sustainability of the practice than in the quantitative sense of power addition.

Repowering for SHP can be conceived in three modalities: rehabilitation, revitalization or expansion (OLIVEIRA, 2017). These are the so-called time lag factors that indicate the possibility of repowering hydroelectric plants. These factors are related, among others, to the wear and tear of structures, sizing obsolescence, and technological lag of a plant; and are responsible for the consolidation of the main energy gains with repowering: flow gains, head gains, efficiency gains, and operational gains (EPE, 2019; OLIVEIRA; BORTONI, 2012).

This allows for optimal exploration (see OLIVEIRA, 2012, p. 34) in projects that have already been built, often undersized, with the following advantages: area with consolidated impacts due to the implementation and operation of the project; minimization of incremental negative environmental impacts; maximization of incremental positive environmental impacts; short-term implementation; power increase within local realities; lower costs when compared to the construction of a new plant; in addition to the possibility of compensation in carbon credits, acquired due to the replacement of thermal energy by hydroelectric energy in the power system.

Concerning attractiveness to the investor, Gomes (2013) estimates 4 to 5 years for a return on capital. This is in agreement with Gyori (2007), who estimated a return time of 4.8 years, and with Oliveira (2012), who estimated an average return time of 5.2 years. This is compared to the return on investment time for new SHP, which is around 10 to 20 years on average.

Some studies of SHP repowering have been carried out in Brazil. The Lajeado SHP, state of Tocantins, had its repowering solution presented by Oliveira and Bortoni (2012), with installed power increasing from 1.8 MW to 8 MW, at a final cost of 3,668 R$/kW; a result achieved without any change in the level of its reservoir. Colferai (2017), for example, found underutilization of flows in the Salto São Luiz SHP, state of Paraná.

Studies conducted in the state of São Paulo highlighted cases with the possibility of quadrupling the originally installed capacity, where Bianchi and Souza (2003) estimated in a simplified way the addition of 117 MW with the repowering of 90 hydroelectric plants, most of them with an average age of 100 years at the time. Veiga and Bermann (2002) reported installed power gains between 21% and 33% for Two decommissioned SHP. Increases of 75% in the Sodré SHP and the inclusion of carbon credits trading to reduce the amortization of the investment were reported by Gyori (2007). On the other hand, the repowering of decommissioned SHP in the regions of Vale do Paraíba and Serra da Mantiqueira, to promote ecotourism and environmental education, additionally to the energy benefit, was addressed by Santos (2007).

Interestingly, recent international experiences confirm repowering as a path to environmental sustainability. In Italy, for example, its contribution to energy independence of local communities, utilization of unused potential, and preservation of historical industrial heritage has been highlighted (GAGLIANO et al., 2014). In Latin America, there are case reports, such as the El Amarillo SHP, in the southern region of Ecuador, whose reactivation/repowering analysis culminated in a capacity of 3.3 MW versus 675 kW, with economic viability, contribution to local development, and reduction of CO_2 emissions (ROMERO-AÑAZCO et al., 2020).

From the above, it is inferred that the preservation of the historical industrial heritage and the promotion of ecotourism or environmental education are still externalities in measuring the environmental benefits of the repowering of SHP that can be reactivated. Another externality is the lack of studies and discussions on the application of environmentally friendly technologies, such as fish-friendly turbines (OLBERTZ et al., 2021; SCHWEVERS; ADAM, 2020; HOGAN et al., 2014), within the scope of repowering/reactivation of small low-head dams. However, such considerations, among others, should constitute a more holistic approach compatible with hydropower sustainability.

Moreover, to the best of the authors' knowledge, SHP has been used for socio-environmental purposes, in addition to power generation in the state of Minas Gerais, for example. The Luiz Dias SHP has been widely used for teaching and extension by the Federal University of Itajubá. The NR SHP helps the fish processing of the company Trutas NR. The Fazenda Boa Esperança SHP, after repowering, started to support agroecological activities and local tourism in the Mantiqueira mountain range.

In summary, all the benefits of repowering are contained in the dimensions of sustainability (environmental, social, and economic). However, it is necessary to pay attention to the internalization of aspects still treated as externalities. This can be done by mapping the interactions that the incorporation of a small hydroelectric plant can promote locally, without disregarding the diversity of perspectives and social actors involved. These interconnections, which are dynamic temporally, can be identified and transformed into opportunities, due to the lesser complexity of these enterprises if compared to large hydroelectric plants.

4 The Theoretical Maximum Gain Method for estimation

Comprehensive repowering feasibility studies can be prohibitive for owners of modest developments due to the risk of non-applicability. Because of the costs involved in surveys, studies, and projects of hydropower repowering, a theoretical analysis of energy benefits can then be carried out. Thus, the method originally proposed by Oliveira (2012) and developed in the present work, for being simple, fast, and low cost, is opportune for local and regional estimates, for the indispensable stimulus advances.

The TMGM consists of this first approach for estimations, using already available data and having as simplifying assumptions the possibility of reaching the maximum theoretical efficiency for the generator sets and or the optimal use of the available inflows and heads.

Figure 1 shows a synthetic model for applying the method. The following information is of interest for the first stage of the method: local hydrology (characteristic flows); topography (head); behavior curves or plate data of the generator sets; dimensional data of the adduction system; historical series of SHP operation (power, efficiency, water levels, generation, availability factor et cetera). Knowledge of the status of the equipment and its remaining useful lives is desirable at this point. In the absence of some of this information, literature data or simplifying assumptions can be used.

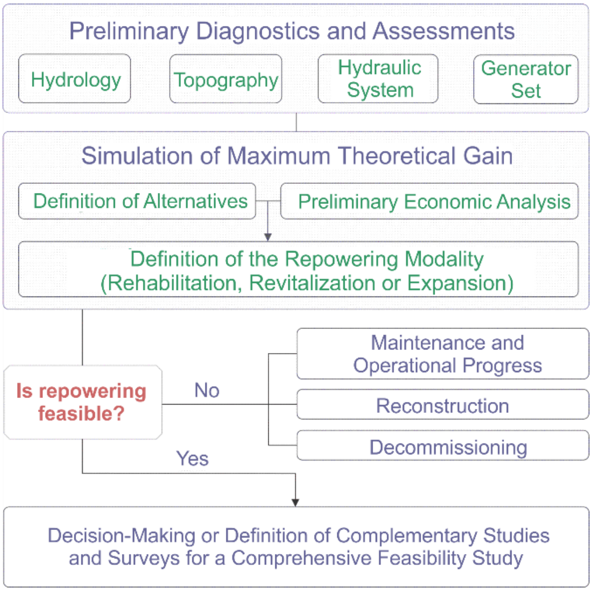
The second step consists of running computer simulations, which include the pre-design of alternatives. Costs are also estimated in this step. The objective function is the optimal use of the hydroelectric potential and the boundary conditions are composed, among other parameters, of technical and environmental constraints for the interventions. The environmental restrictions can be impeditive only if there is an increase in the level of the reservoir; for SHP, normally dimensioned on a run-of-river basis, from a simple derivation of the river, environmental impediments of this nature would be the exception.

The design power of a SHP is given by the equation

$$P = \eta_{ap}\, \delta\, Q_p\, H_B \qquad (1)$$

where, P is the installed power (W); η_{ap} is the overall efficiency of the plant (dimensionless); δ is the specific weight of water (N/m³); Q_p is the design flow (m³/s); and H_B is the gross head (m)

Figure 1 - Stages for applying the TMGM



Source: Authors' elaboration.

The results obtained will indicate the convenience of repowering and the most appropriate modality for its materialization, which according to Oliveira (2018, 2017, 2012) can be of three types: rehabilitation, revitalization, or expansion. From there, one can proceed or not with a complete technical, economic and environmental feasibility study, with the definition of the surveys, tests, and complementary specialized studies, necessary to subsidize it. The full environmental studies are developed in this subsequent stage. If repowering is not feasible, the options are maintenance and continued operation, reconstruction, or decommissioning, depending on the case. Therefore, the proposed method supports decision-making.

5 Results and Discussion

5.1 Description of the Bagagem SHP

Bagagem SHP is in operation on the Bagagem river, in sub-basin 22, in the Tocantins river basin, at coordinates 11º22'17"S and 47º34'32"W, in the municipality of Natividade, state of Tocantins. The area of the Bagagem river basin totals 158.5 km² and the drainage area contributing to the exploitation is 130 km². Its construction started in 1970 and was finished in 1977. Its concession power is 480 kW and it is interconnected, through its substation, to a 34.5 kV transmission line. The general arrangement of the Bagagem SHP is represented in Figure 2.

Figure 2 - Aerial photo of the Bagagem SHP

Source: Naturatins (2010).

5.2 Theoretical Maximum Gain Method applied to the Bagagem SHP

This section explains the strategies and techniques used to indicate the optimal exploration for repowering Bagagem SHP. The main ones are the criteria for dimensional analysis and definition of the maximum capacity of the components of the current adduction system; the use of the average capacity factor of hydroelectric plants in operation in Brazil; and the use of the long-term mean flow to estimate the maximum theoretical potential, in the absence of the flow permanence curve.

It is worth noting that, due to the unavailability of information, it was not possible to fully establish the boundary conditions related to the original sizing of the project. This was circumvented by the use of public interest data declared by the owner to ANEEL and the environmental agency of the state of Tocantins, by prior knowledge of the site, and by the use of Geographic Information Systems - GIS, in addition to conservative estimates compared to the specialized literature.

The knowledge of the consequences of the time lag factors on the enterprise and the limited reliability of the available data led to the adoption of conservative values for the evaluations. The simulation of the theoretical maximum gain was performed by applying the classical dimensional equations involved. Excel software was used for the dimensional quantifications and variation of the input data - design flow rate, head and energy losses.

Three repowering alternatives were sized. The incremental power for each new arrangement was then calculated. The cost projection was done using cost curves available in the literature, economically updated. Next, a cash flow was generated for each alternative, for a 20-year horizon, culminating in the calculation of the return on investment time. Finally, the gains were estimated and it was possible to define the necessary studies and surveys for the next stage, which will broadly delineate the repowering.

5.2.1 Stage 1: Diagnostics and Assessments Preliminary

Only a partial history of the flows for the project was available, including the long-term average flow, Q_{LT}=3.77 m^3/s, and the average flow, $Q_{average}$=5.30 m^3/s (NATURATINS, 2010). Since the local topography was not available, the expedite knowledge of the area of the project allowed the conjecture of realistic layouts. The plant has a small dam, built in reinforced concrete, of the free overflow type, for water derivation only. This structure has a maximum height and length equal to 1.34 m and 20.60 m, respectively. Its adduction system is composed of an intake, adduction channel, forebay tank, and penstock.

The power house hosts a Francis turbine of 330 kW and an electric generator of 600 kW. The maximum current generation power is around 200 kW on average (NATURATINS, 2010) and, compared to the concession power, 480 kW, there is an underutilization of 58.33%, mainly due to the restrictive capacity of the turbine.

The dimensional analyses of the original hydraulic adduction system revealed a maximum permissible flow of 3.08 m^3/s for the channel and 2.90 m^3/s for the penstock, respectively. The channel has a rectangular reinforced concrete section and the penstock is made of steel with a circular section. It is concluded that both the channel and the penstock are not restrictive for reaching the concession power, however, the penstock does not present a gap for increasing the adduced flow. The forebay tank (for more information see OLIVEIRA, 2012) could not have its capacity confirmed due to lack of data and, thus, it was taken as a simplifying hypothesis that it is adequately sized.

5.2.2 Stage 2: Simulation of Theoretical Maximum Gain

New hydroelectric exploitation: definition of alternatives

Due to the unavailability of the flow permanence curve and the inapplicability of conducting a hydrological study in this specific case study, the Q_{LT} was considered in the calculations for a conservative estimate of the new installed capacity. As the penstock is undersized (2.90 m^3/s) in relation to the tributary flows, a flow gain of at least 0.87 m^3/s is expected, taking the Q_{LT} as a reference. The remaining flow rate of 25% of Q90, defined by Naturatins Administrative Rule n° 904 of 2008, should be considered later in the feasibility study and be maintained downstream of the project throughout.

The originally used gross head, H_B, is 28.14 m. Being the gross head defined as the difference between the maximum normal upstream level and the normal downstream level. From previous knowledge of the enterprise site, a possible gain of 4.55 m was verified. Thus, a new gross head of 32.69 m can be used for repowering arrangements.

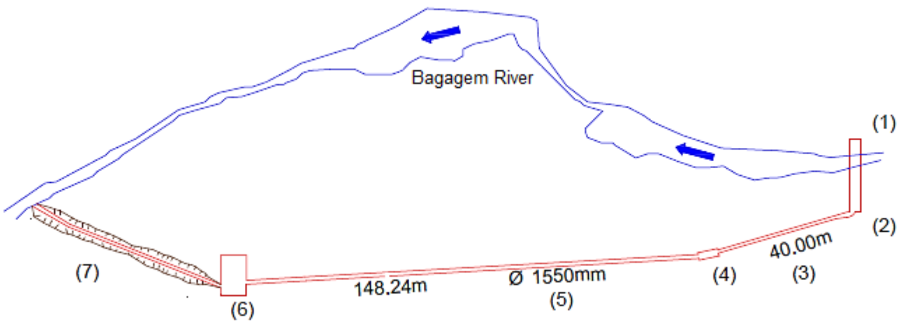
In the energy sizing we initially adopted a capacity factor, FC, consistent with those normally performed by SHP in operation in Brazil. The capacity factor is defined as the ratio between the average power and the installed power. In possession of the Q_{LT} an FC=0.65 was used to define the maximum theoretical installed power, with respective design flow, Qp, of the order of 5.80 m³/s. For this application three alternatives were established, detailed below.

Alternative 1 - Full use of the existing head and flow

This alternative, in the expansion modality, is consolidated with the implementation of a new arrangement that completely substitutes the current one. It includes the implementation of a dam (upstream of the current one), a hydraulic adduction system (intake, channel, forebay tank and penstock), an power house and a restitution channel, as shown in Figure 3. For full use of the available hydraulic potential, that is, H_B=32.69 m and Q_p=5.80 m³/s, there is no restriction for sizing.

Figure 3 - Schematic plan of Alternative 1

Components	Arrangement 1
Dam	(1)
Intake	(2)
Channel	(3)
Forebay tank	(4)
Penstock	(5)
Power house	(6)
Tailrace	(7)



Source: Authors' elaboration.

The new projected dam is of the free overflow type, where local characteristics favor its construction, e.g. the presence of a narrow valley and bedrock. It is cast in concrete, 24 m long and 1.80 m high. The flood flow found for a return time of 100 years is 22 m³/s. This resulted in a maximum overflow of 0.59 m at the spillway. Since it is a derivation SHP, there is no reservoir and even the floodable area is restricted to the river channel. The installed power of this alternative totals 1,535 kW.

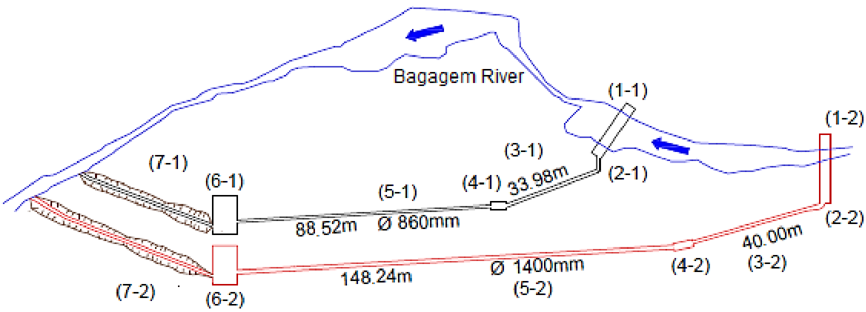
Alternative 2 - Maintain the current arrangement with the insertion of a new hydraulic system

Alternative 2, also in the expansion modality, is established by maintaining the current gross head of 28.14 m and conserving the existing adduction system and the power house; at the same time an adduction system and an additional power house will be built for the use of the new gross head of 32.69 m. Therefore, the construction of a dam upstream of the current one with the same dimensions as alternative 1 is foreseen, for the adduction of the remaining project flow.

As the current turbine flow is only 1.23 m³/s, the remaining flow of 4.57 m³/s has been allocated to the new adduction system and additional power house. This results in an incremental installed capacity of 1,208 kW. The arrangement of this alternative is shown in Figure 4.

Figure 4 - Schematic plan of Alternative 2

Components	Arrangement 1	Arrangement 2
Dam	(1-1)	(1-2)
Intake	(2-1)	(2-2)
Channel	(3-1)	(3-2)
Forebay tank	(4-1)	(4-2)
Penstock	(5-1)	(5-2)
Power house	(6-1)	(6-2)
Tailrace	(7-1)	(7-2)



Source: Authors' elaboration.

Alternative 3 - Maintain the current arrangement with complete replacement of the generator set

The verification of the underutilization of the maximum allowable flow (2.90 m³/s) in the existing hydraulic system and the proof that the hydraulic turbine is restrictive indicated the opportunity to evaluate the replacement of the generator group in operation. This repowering alternative is in the revitalization mode, since it consists of the complete substitution of the generator group, conserving the existing dam, adduction system and power house, and leading to a condition higher than the concession power limit (480 kW). Thus, with Q_p=2.90 m³/s and H_B=28.14 m we arrived at an installed power of 615 kW.

Preliminary Economic Analysis

The economic analysis is simplified under the TMGM. If this initial valuation indicates the desirability of repowering, in the hierarchy of analyses, the next step is the feasibility study with a refined economic evaluation.

In the case analyzed, the initial projection of costs, related to the acquisition of materials, equipment, and services for the works, was made through equations (SOUZA et al., 1999). Consequently, the costs for the penstock, generator set and power house were estimated using the equations developed by Magalhães (2009); the cost for the small dam was determined using the equation by Martinez (1994); and, finally, the equations proposed by Souza et al. (1999) were used in a complementary way. While these equations are for the base years 2008, 1994, and 1998, respectively, the economic update for the year 2019 was performed with support from the Index for Civil Construction in Brazil - INCC.

The gross annual revenue was predicted using the following equation

$$RA = \delta \, Q_p \, H_B \, \eta_{ap} \, FC \, t \, T \, 10^{-3} \text{ (R\$)} \quad (2)$$

where, RA is the gross revenue (R$); t is the time considered (h); T is the price of electric energy (R$/kWh).

The energy sale price was 0.32 R$/kWh, applied to the North region of Brazil, in the period considered. It was adopted an annual unavailability period of 48 hours for alternatives 1 and 2 and 96 hours for alternative 3, after the works for the increase in power. Subsequently, a cash flow was prepared for each alternative, with annual economic inputs and outputs, considering only the incremental costs and revenues arising from repowering (OLIVEIRA, 2012).

Once the calculations of the annual inputs and outputs were performed, the annual net benefit, BA, was quantified, which is given by the following relationship: BA = RA - CA. CA is the annual cost. Therefore, to quantify the gain in the project horizon, the sum of the annual benefits was made, excluding the costs with taxes, insurance and depreciation for a project horizon of 20 years.

Therefore, the simple payback (TR) was adopted to quantify the payback period of the investment, which can be expressed by the following relation TR=I/BA, where I is the total investment (without interest). In Table 1 the results of the economic estimate are synthesized and it can be seen that alternative 3 is the most economically viable.

Table 1 - Summary of the results of the preliminary economic analysis

Alternatives	*Investment (R$)*	*Payback (years)*
1	10,502,200.64	6.79
2	7,374,825.56	6.93
3	3,220,485.05	3.45

Source: Authors' elaboration.

Definition of the repowering modality and decision-making

The three alternatives considered have advantages and disadvantages that should be weighed to indicate the best alternative. Alternatives 1 and 2 are in the expansion modality and alternative 3 is in the revitalization modality. Interestingly, there will be no unavailability of SHP during the construction period of the amplified part in alternatives 1 and 2, due to the possibility of constructing the new dam without cutting off the supply to the existing hydraulic system, made possible by a simple deviation of the river.

The negative environmental impacts of alternatives 1 and 2 are minimal, since the new dam is only for diverting water from the river (no reservoir). There will still be the need for the suppression of part of the vegetation in the route of the expanded part, with corresponding compensation. However, this area already has consolidated environmental impacts due to the presence of the undersized project and the various economic and socio-environmental benefits of the repowering, already presented in this text, are greater.

Among the advantages of alternative 3 are the reduced future unavailability of the SHP, since the replacement of the generator set will reduce the need for shutdowns; increased useful life; reduced operation and maintenance costs of the generator set; minimal negative environmental impacts, which would result only from modifications in the power house. On the other hand, the need to integrate the new equipment to the current system would result in the unavailability of the SHP.

It should be added that beyond the strictly economic conclusion that Alternative 3 is the most attractive, the TMGM revealed that repowering the Bagagem SHP is feasible and justifies the investment for a technical, economic and environmental feasibility study, and that all three alternatives should be rigorously evaluated in this second phase.

The complementary studies and surveys required for the full feasibility study are the following: an updated hydrological study; a topographical survey of the area, for expansion; an environmental study; and geological and geotechnical studies. Furthermore, the capacity of the substation to be implemented must be defined, as well as the need or not to expand the capacity of the associated high voltage transmission line. And finally, all alternatives require regularization with ANEEL, because of the change in the installed capacity of the concession.

6 Conclusions

Although we talk about technical, economic, and environmental gains when making a decision about the repowering of a hydroelectric plant, all these benefits are of an environmental nature, in its physical, biotic, and socioeconomic aspects. Because of the particular relationships of a hydroelectric plant with its environment, more than a strategic environmental vision, it is necessary to approach repowering in terms of the dimensions of sustainability. In this sense, although all the benefits of repowering are contained in these dimensions, both from the entrepreneur's point of view (Triple Bottom Line) and from the point of view of the temporal interest of the collectivity (sustainable development), it is essential to adopt systemic approaches for the internalization of aspects still treated as externalities.

The Theoretical Maximum Gain Method, developed in this work, allows estimating the benefits of repowering a hydropower plant in a fast, simple, and low-cost way. And, consequently, it allows the projection of regional estimates of sets of enterprises, for subsequent prioritization of the best opportunities. Advances in this sense have the purpose of maximizing sustainability in the insertion of these hydroelectric plants in the socio-environmental context of their surroundings, which, contemporarily, should be guided by the environmental, social, and economic dimensions in detriment of the exclusively economic vision. Especially due to the urgency of new positions in the face of the global climate crisis.

The application of the method at the Bagagem SHP allowed the establishment of realistic repowering alternatives and, for a first economic approach, even with the adopted simplifications, alternative 3 proved to be more attractive due to the shorter payback time. However, if the other benefits are considered, it is inferred that all alternatives are viable compared to the option of implementing new hydroelectric plants, and should be considered in the integral feasibility study, which is the next step in the hierarchical evaluations.

Therefore, the benefits of repowering in comparison with the installation of new enterprises are indisputable. It is worth pointing out that the greatest benefit is that the repowering guarantees the optimal use of natural resources before the temporal dynamics of the systems involved and is a concrete instrument for sustainability and, consequently, should have a more imposing character, instead of depending exclusively on the opportunity decisions of entrepreneurs. However, for this, governmental stimuli are indispensable, especially with regard to the guarantees of recognition of the energy added and the solution to the regulatory gap existing in Brazil.

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AMBIENTE & SOCIEDADE 25 anos años years

A sustentabilidade como perspectiva para repotenciação de pequenas centrais hidrelétricas no Brasil: método para estimativas

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São Paulo. Vol. 25, 2022
Artigo Original

Resumo: A repotenciação é uma opção sustentável para hidrelétricas relativamente antigas. Contudo, ainda encontra-se em um processo de desenvolvimento dos seus aspectos técnicos, socioambientais e regulatórios, no Brasil. Além disso, existem poucos trabalhos disponíveis na literatura sobre o tema. Uma lacuna da área é a falta de metodologias que direcionem a mensuração dos benefícios nos empreendimentos aptos, para priorização dos mais oportunos, redução dos riscos e incentivo dessa prática no âmbito nacional, regional e dos agentes. Neste trabalho apresenta-se uma discussão teórica das práticas atualmente empregadas e propõe-se um método acessível (simples, rápido e de baixo custo) para suporte à tomada de decisão quanto à aplicabilidade da repotenciação em pequenas centrais hidrelétricas. Os resultados explicitam a sustentabilidade ambiental da prática frente às limitações e desafios que envolvem a construção de grandes hidrelétricas, atualmente.

Palavras-chave: Sustentabilidade, Repotenciação, Pequenas Centrais Hidrelétricas, Ganho Máximo Teórico, Aproveitamento ótimo, Reforma, Aumento de capacidade, Recursos renováveis.

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La sostenibilidad como perspectiva para la repotenciación de pequeñas centrales hidroeléctricas en Brasil: método para estimaciones

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São Paulo. Vol. 25, 2022
Artículo Original

Resumen: La repotenciación es una opción sostenible para centrales hidroeléctricas relativamente antiguas. Sin embargo, aún está en proceso de desarrollar sus aspectos técnicos, socioambientales y regulatorios en Brasil. Además, hay pocos trabajos disponibles en la literatura sobre el tema. Una brecha en el área es la falta de metodologías que orienten la medición de beneficios en emprendimientos adecuados, para priorizar los más oportunos, reducir riesgos y fomentar esta práctica a nivel nacional, regional y de agentes. Este artículo presenta una discusión teórica de las prácticas actualmente empleadas y propone un método accesible (simple, rápido y de bajo costo) para apoyar la toma de decisiones sobre la aplicabilidad de la repotenciación en pequeñas centrales hidroeléctricas. Los resultados demuestran la sostenibilidad ambiental de la práctica ante las limitaciones y desafíos que implica la construcción de grandes centrales hidroeléctricas, actualmente.

***Palabras-clave*:** Sostenibilidad, Repotenciación, Pequeñas Centrales Hidroeléctricas, Máxima Ganancia Teórica, Aprovechamiento óptimo, Remodelación, Aumento de capacidad, Recursos renovables.