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INTEGRATION OF MICRO HYDROPOWER PLANTS IN A MULTIPURPOSE BRIDGE-DAM IN THE RURAL AMAZON

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Abstract. *A major problem in rural Amazonia is the supply of electricity, justified by the difficulty of access to communities, high cost of transmission and distribution of energy to small populations. Even with the expansion of the rural network, the cost of energy is a major problem for the economic development of these communities. In addition, the road network crosses several small watercourses, with access restricted to small wooden bridges, which makes logistics difficult for the flow of agricultural production from existing communities. To meet this energy demand, the small-scale supply model, mainly with the implementation of small hydroelectric plants (SHP), has proved to be a good alternative. It is proposed here to replace a wooden bridge with a concrete bridge/dam, including a SHP integrated into the bridge structure. The subject is scarce in the literature and this project analyzed the implementation of this technology in a small bridge in the southeast region of Pará. The SHP used two propeller-type hydraulic turbines with number and size defined from local hydrological study, along with turbine efficiency, in order to meet the demand of the community where it will be installed.*

Keywords: *turbine, bridge, small hydroplant*

1. INTRODUCTION

The Amazon is recognized worldwide as one of the richest regions in terms of biodiversity and natural resources on the planet. Its extensive hydrographic network composed of large rivers offers great potential for generating electricity. Despite this, the region faced major challenges in terms of access to electricity, especially in remote and isolated areas, due to the costs of installing transmission and distribution integrated into the national electricity grid (Duarte et al., 2010). And these challenges have created a major obstacle for productive activities, which are mainly related to primary value-added production, for example, rice, mandioca and fruits. To meet this demand for energy, the small-scale supply model. In this line, researchers and professionals in the area have been studying small hydroelectric power plant (SHP) projects to take advantage of the potential of small rivers in the region, using run-of-river hydraulic turbines (HT) to generate electricity. These machines appear as a promising solution for taking advantage of the region's hydroenergetic potential. Unlike large hydroelectric plants that require the construction of large dams and reservoirs, run-of-river HTs are designed to operate in rivers with ultra-low head and variable flow. Blanco et al., (2008) already indicated this technology to generate energy in remote areas of the Amazon, based on a previous study of the local hydrology proposed by the authors. Later, Quintas et al., (2012) studied the supply of electricity to a rural community in the Amazon through the implementation of Micro Hydroelectric Plants (MHP) in small rivers in the region, presenting technical evaluations of cost-benefits. Vinagre (2016) studied the technical-economic optimization of low head SHP electrical generation in the Amazon. Ismail and Lino (2015) investigated a cheap hydrokinetic turbine for use in rivers in the Amazon to ensure access to electricity for remote communities. More recent studies investigated the hydrokinetic potential of Amazonian rivers (Santos et al., 2019); (Oliveira and Vestena., 2022) and stated that the energy generated by conventional SHPs in the Amazon could be harnessed with low-rise TH (Chaudhari et al., 2021), encouraging the exploitation of small rivers to serve isolated communities. At the same time, isolation in the rural Amazon is aggravated by the poor existing

infrastructure. Currently, most of the roads are dirt, with countless wooden bridges and footbridges over the rivers, which are extremely deteriorated, some in danger of imminent failure, harming the logistics of transporting agricultural products, the safety of people, and the environment. Development of the region. In this context, two problems can be seen that can be solved jointly: the replacement of old wooden bridges by concrete bridges coupling a SHP composed of run-of-river HT for the use of small rivers in the Amazon. In the aforementioned studies, this is a subject that has been little researched and deserves attention. Therefore, the objective of this work is to present a methodology that aims to replace wooden bridges with a concrete bridge/dam, including a SHP integrated into its structure, to take advantage of the potential of small rivers in the Amazon, with very low head and great flow variation, for the generation and autonomy of electric energy in remote communities, for greater security in the transportation and disposal of production and development of the region. Initially, the study of the hydrological site where the plant is intended to be built is necessary. This step is fundamental to define the characteristics of the water body (flow and head), which will define the specific operation configurations of the HT. Then, data from a real machine are parameterized and, from the application of the similarity law, it is possible to identify the number of turbines of adequate size to the potential of the exploited site. This methodology was implemented in a remote community in the northern region of Brazil, which has a local enterprise with a need for electricity and an access infrastructure, with a wooden bridge in very poor condition. With the replacement of the bridge, it was suggested to operate two HT in parallel to take advantage of the potential of the local hydrological site. The estimated energy generated exceeds the energy demanded by the project. In addition, the concrete bridge/dam provides safety and agility in the transportation of production.

2. METHODOLOGY

This paper presents a methodology for the utilization of the potential of small Amazonian rivers of high drop and high flows for the generation of electricity, from the installation of TH in facilities attached to concrete bridges / dams instead of wooden ones. Fig. 1 illustrates the proposed methodology and its order of execution, for application in the studied region. In the following, the steps will be described in detail.
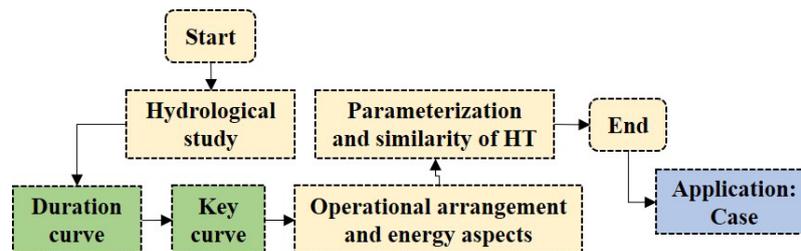

Figure 1. Stages of the proposed methodology and its application.

2.1 Hydrological study

The hydrological processes have random behavior observed in historical series, representative and reliable, obtained in fluviometric stations (FE) installed in river basins (BH). These data are organized and expressed in curves that represent a water body of a given BH basin. Unfortunately, hydrological data, in many cases, are difficult or non-existent, due to the high costs inherent in the implementation, operation and maintenance of hydrometric network, especially in the Amazon region, where logistics and natural barriers increase the costs of these systems (Costa et al., 2012). To circumvent this difficulty, this study used a model developed by Blanco et al., (2005) of rainfall-runoff adapted for small BH of the Amazon region, to determine the flow-duration curves, important for the design of energy production in MHP, since the facilities for ultra-low drop in small rivers are more suitable for this region due to its flat topography.

2.1.1 Permanence curve

The permanence curve (PC) is defined as the relationship between the magnitude and frequency of flows for a BH, providing an estimate of the percentage of time that the flow can be equaled or exceeded in the historical period. To build a CP, initially one should select fluviometric stations in operation located in the analyzed BH, considering historical series of flows for the longest period of observations possible. When available, these data can be easily obtained from the hydrometeorological database of the National Water and Sanitation Agency (ANA), on the HidroWeb portal. In electronic spreadsheets, the data should be organized in a descending manner, associating to each value an exceeding frequency and an empirical plotting possibility.

2.1.2 Rating curve

The rating curve (RC) of a river relates the height of the water table to its corresponding flow at a given point over time (Malik et al., 2021). This is an important tool for the hydrological and hydraulic analysis of a watercourse, allowing to understand its behavior, predict floods and floods, and assist in the planning of works and projects related to water resources. The preparation of the RC requires data collected in the field or at hydrometric stations that record the flow and water height (elevation) over time. The head of the water body determines the points for taking flow velocities, which are usually collected with specific equipment. The data collected for each measurement period is then organized in electronic spreadsheets to plot a QxH graph (flow and gross height). Then, the curve must be adjusted by mathematical regression, using the function that best fits the collected data. Finally, you can use the relationship to predict water levels based on flow or height.

2.2 Operational arrangement and energy aspects

Based on the analysis of the PC and RC, this study considered run-of-river schemes with parallel turbines, aiming to better take advantage of the seasonality inherent to the Amazon region (Blanco et al., 2008). This configuration uses a small dam attached to the bridge to ensure the minimum height for power generation, but still configuring the plant to be run-of-river, avoiding the ponding of large areas and the simplicity of low-cost design. The excess flow of the river continues through a spillway, which had its dimensioning disregarded. Regarding the number of turbines, two were considered operating peralently, with the design flow rate Q_1 (larger turbine) and Q_2 (smaller turbine), being Q_T is the total design flow, according to Eq. 1. If the river flow allows, the arrangement works with the most powerful turbine operating in the period between the end of the flood and the beginning of the low flow, while the smaller turbine operates during the low flow. In the flood, the THs run at the same time producing electricity.

$$Q_T = Q_{1+} Q_2 \tag{1}$$

Generally, it is assumed Q_T equal to $Q_{95\%}$ (PC) is usually assumed for hydroelectric projects, as it guarantees constant power for 95% annual operation of the plant (Quintas et al., 2011). However, for small Amazonian rivers, low flows generate small powers, which do not meet local demands from very small machines. Therefore, it is necessary to assume a higher design flow of $Q_{95\%}$. In addition, it is necessary to pay attention to the operating range of the turbine, which can influence the efficiency of the machine, therefore, the power generation. The power generated with turbine operation is determined by Eq. 2, where **P** is the turbine power [kW], **Q** is the flow [m³/s], **ρ** is the density [kg/m³], **H** is the gross drop [m] (defined in RC), **g** is the acceleration of gravity [m/s²] and **η** is the efficiency of the machine. To estimate the energy generated, 5% of days in a year of operation were discounted for possible maintenance or replacement of turbines.

$$P = \frac{Q.H.\rho.g.\eta}{1000} \tag{2}$$

2.3 Parameterization and similarity of hydraulic turbines

The limited capacity of conventional TH to exploit low headwater flow is one of the barriers in the use of these machines in small rivers, requiring high investments (Muis et al., 2015), making them, in most cases, uneconomical due to their large sizes. To overcome this limitation, TH parameterization presents itself as an excellent solution. This is a process of defining the dimensionless parameters and characteristics essential for efficient design and operation in a given application, reducing the number of experimental variables affecting a given physical phenomenon, by means of a compaction technique. Eq. 3 shows the dimensionless parameters, where **ψ** is the pressure coefficient, **ϕ** is the flow coefficient, **λ** is the turbine power coefficient, **δ** is the diameter coefficient, **Y** is the specific energy, **u** is the blade tangential velocity, and **Cm** is the meridian velocity.

$$\psi = \frac{2Y}{u^2}; \quad \varphi = \frac{C_m}{u}; \quad \lambda = \psi \times \varphi \times \eta; \quad \delta = \frac{\psi^{\frac{1}{4}}}{\varphi^{\frac{1}{2}}} \tag{3}$$

The main objective is to optimize the turbine performance and efficiency at different sizes, ensuring the safe and reliable operation of the system for a specific situation (Morani, 2018). For this work, data from a turbine experimented by Samora (2016), a five-bladed tubular propeller type with axial flow, were parameterized, with data presented in Table 1. Once parameterized, in order to define the size of a turbine to explore a specific site, the turbine similarity law was applied, which is based on the principle that the hydrodynamic behavior of a TH in reduced scale is similar to the behavior of another one in real scale, provided that the similarity conditions are met, i.e. geometry, specific speed and Reynolds number. Eq. (4) expresses the similarity law, where **Q** is the flow rate, **N** the rotational speed, **Y, D** the diameter, **P** the power, **ρ** the density of the liquid and **η** the efficiency of the machine.

$$\frac{Q_1}{Q_2} = \frac{n_1}{n_2} \times \left(\frac{D_1}{D_2}\right)^3 \qquad \frac{Y_1}{Y_2} = \left(\frac{N_1}{N_2}\right)^2 \times \left(\frac{D_1}{D_2}\right)^2 \qquad \frac{P_1}{P_2} = \frac{\rho_1}{\rho_2} \times \left(\frac{n_1}{n_2}\right)^3 \times \left(\frac{D_1}{D_2}\right)^5 \tag{4}$$

Table 1. Parametrized turbine in this study.

DIMENSIONAL PARAMETERS	
D [m]	0,0848
N [rpm]	1000
Q [m³/h]	35
H [m]	2,55
η [%]	49

Source: Samora et al. (2016)

2.4 Case study

The proposed methodology was applied to the Igarapé água preta, a water body in the community of Janarí, district of Janarí, located 70 km from its headquarters, the municipality of Goianésia do Pará, in the southeast of Para, Amazon region. The district has a total area of 2,138 km² and a population of 5,000 inhabitants. The water body has high flow and low fall and belongs to the Tocantins-Araguaia hydrographic basin, with a total area of 21 km². Janari enjoys a small cassava flour agroindustry, which is managed by a local association. With the modernization of the industrial input, the monthly industrial demand for electricity was estimated at 3.420,45 kWh/month. Fig. 2 shows the location of Pará in Brazil and Janari in Pará (a), the detail of Janari (b), the black water stream and the wooden bridge (c) and the local flour house (d).

Figure 2. Location of Pará and Janari in Brazil (a), detailing Janari (b), Água Preta creek and wooden bridge (c) and flour house (d).

The road infrastructure for access to the community is typically dirt roads with numerous wooden bridges and pontoons, which are extremely deteriorated, some in danger of imminent breakage. Over the Igarapé there is a wooden bridge in very poor condition. Bridges are structures that have the primary purpose of providing a means for pedestrians, animals and vehicles to cross obstacles in the landscape. The materials used for bridge construction are usually wood or concrete. Concrete is increasingly being used over wood in bridges across the country. Two main advantages make concrete bridges viable structures to receive HT installations: mechanical strength, shock resistance and vibration resistance. The most suitable types of hydraulic turbines to be used on concrete bridges are run-of-river or low-fall plants (Quaranta, 2022). By replacing the wooden bridge with a concrete one, with attached infrastructure for an SHP, it is envisioned to provide electricity autonomy for this community enterprise and to ensure the safe flow of production and transportation in general. The Fig. 3 shows an example of a concrete bridge suited to receive a hydroturbine installation. The space below the haul road can be used for installing the turbines. These spaces will be continuously underwater to a certain level. Depending on river flow conditions, gates can also be set up to keep the water at a certain minimum level.
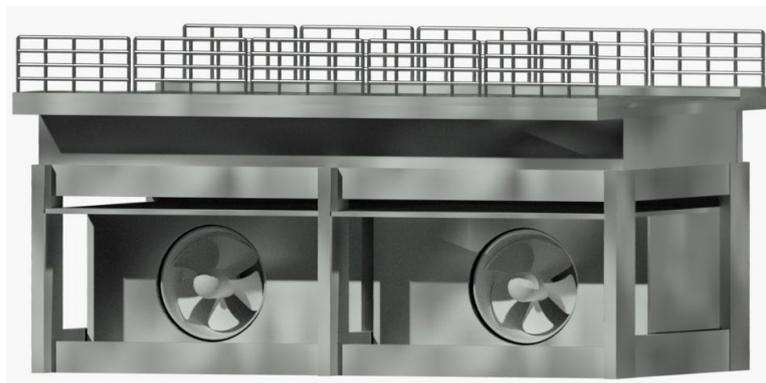
Figure 3. Example of concrete bridge where a turbine could be mounted

3. RESULTS

For the creation of the PC (Fig. 4), data from fluviometric station n° 31020000, Tracambeua waterfall, were selected on the HidroWeb portal. With the data collected in visits to Janarí, particularly in Igarapé Água Preta, and the setting of an upstream quota of 4.20m with the installation of the bridge/dam, it was possible to elaborate the RC (Fig. 4(b)). The suggestion to replace the wooden bridge defined the location of the concrete bridge/dam, unlike Quintas et al., (2012) who chose the SHP site based on the leveling of the land.
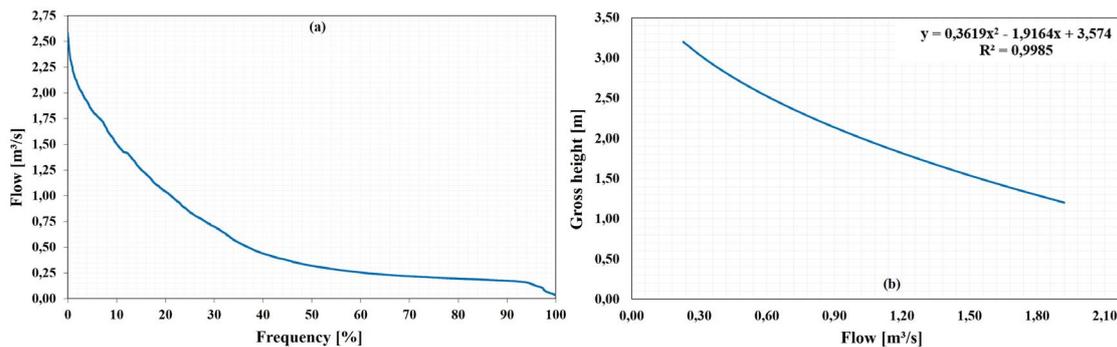

Figure 4 – Permanence curve (a) e Rating curve (b) of igarapé água preta – Janari

3.1 Hydraulic turbines in parallel

Two turbines were parameterized. The chosen operating range defines that the minimum flow is 75% of the machine's flow and the maximum 115% (Table 2), for a maximum efficiency of 60% (Samora et al., 2016). The SPH system was designed with two turbines operating in parallel as Q_1 and Q_2, in order to better take advantage of the seasonality characteristic of the Amazon region. Assuming that the design flow rate Q_1 is equal to $Q_{50\%}$ and Q_2 equal to $Q_{75\%}$, the Q_T (total flow rate of the project) will be the sum of the two, operating in parallel. In addition, the system will continue to operate when the stream Igarapé flow becomes less than Q_1, having its lower design flow equal to Q_2. Q_1 will run for a period of six months and Q_2 for nine months of the year. The use of the turbines is defined by the precipitation in the region, with the first operating during the period of greatest incidence of rain and flooding of the river, January to June (Blanco et al., 2005). The turbine 2 operates with lower flows, therefore, longer times during the year, reaching the $Q_{95\%}$ of the igarapé, guaranteeing the generation of energy and the service to the enterprise in periods of low flow. It will be in operation during the dry periods of the stream, july-december, and operating in parallel with Q_1 in the first months of the year, Jan-Mar. The chosen configuration is the same as by Quintas et al., (2012) and Blanco et al., (2008), as it provides greater use of winter floods with the two turbines operating in parallel. It is worth noting that the difference between the present study and these two works is the use of parameterized data from real turbines.

Table 2. Operating range.

Q_1		Q_2	
Q_1 [m³/s]	0,31	Q_2 [m³/s]	0,20
Q- [m³/s]	0,21	Q- [m³/s]	0,14
Q+ [m³/s]	0,35	Q+ [m³/s]	0,23

When the flow of Igarapé Água Preta is above the upper value (Q+) in the adopted operating range of Q_1, the plant will have both turbines operating in parallel, when it is below the lower value (Q-), it will only operate with the second turbine, at flow rate Q_2. The flow that is not being turbined will be poured through the overflow. The parameters of the new turbines are presented as **D** external diameter, **d** internal diameter, **R** radius, **A** the area, **N** rotational speed, **ω** the angular coefficient, **u** the tangential velocity, **Cm** the meridian velocity, **Q** flow, **Y** the specific energy and **H** There is the gross fall (Table 3). The operation of the turbines is exemplified in Fig. 5.

Table 3. Parameterized turbines.

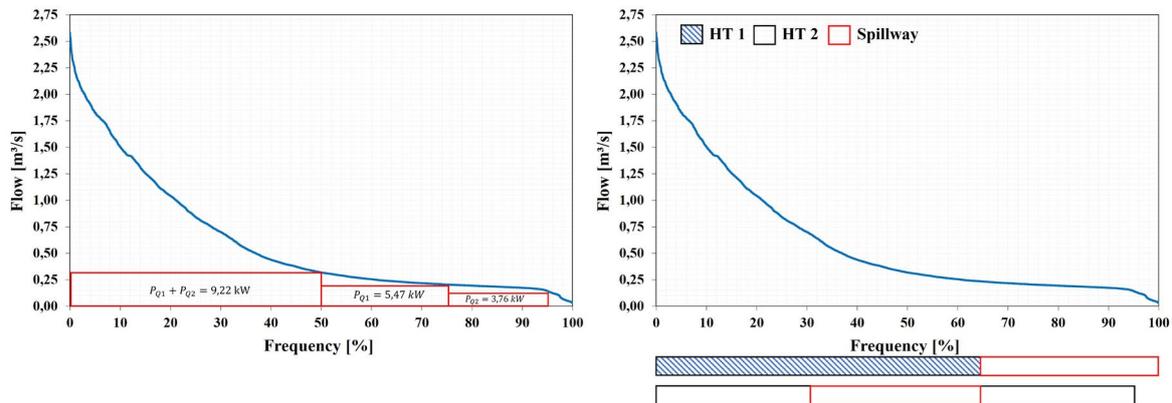| Q₁		Q₂	
D [mm]	460	D [mm]	365
d [mm]	230,54	d [mm]	182,93
R [m]	0,23	R [m]	0,18
A [m²]	0,12	A [m²]	0,078
N [rpm]	200	N [rpm]	260
ω	20,95	Ω	27,22
u	4,82	u	4,97
Cm	2,50	Cm	2,57
Q [m³/s]	0,31	Q [m³/s]	0,20
Y [m²/s]	29,43	Y [m²/s]	31,31
H [m]	3	H [m]	3,20

Figure 5. HT operation in parallel

The energy demand of the flour house was estimated based on maximum demand, that is, with all equipment working simultaneously. The SHP operates 95% of the days of the year, with an 18-day break (5%) for possible maintenance. The estimated power generation was 47,957.63 kWh/year (Table 4), meeting the demand of the Janarí flour house, with a total of 41.04 kWh/year. If the plant requires maintenance for a prolonged period, Quintas et al., (2012) suggests that the community be supplied by other energy sources, such as wind, solar or generators. Evidently, the third is not attractive for burning fossil fuel. In addition, the use of SHP is the most favorable option for these cases, as it is an already consolidated technology and, in addition, a more concentrated source than wind and solar energy. At the same time, their installation in rural areas offers benefits to the communities served (Blanco et al., 2008), such as electricity autonomy for the enterprise, providing greater competitiveness in the market, and leveraging the economy and community development. Although there are negative impacts with its installation, such as the flooded area, machine noise, etc., its effects are minimized by the size of the installed project, as it is a small plant.

Table 4. Generated power and energy

	Q₁ [m³/s]	Q₂ [m³/s]	Total
P [kW]	5,47	3,76	9,23
E [kWh/year]	23.623,49	24.334,14	47.957,63

4. CONCLUSIONS

This study presents a case study for taking advantage of the potential of small Amazonian rivers with ultra low head and variable flows. By replacing a wooden bridge with a concrete one with a SHP attached. With the replacement, the region will enjoy greater security in the transport and flow of production and development in the region. From the point of view of sustainable development, it is a good alternative, generating energy from a renewable source, causing low impact on the environment and generating jobs that contribute to leveraging the economy and social development of the region. The system, with two turbines operating in parallel, offers the advantage of taking advantage of the period of greater precipitation and floods. Thus, it is possible to supply the electricity demand of a small cassava flour agroindustry, the enterprise that was the focus of the case study, in its entirety throughout the year. If prolonged maintenance is required and exceeds 18 days of plant downtime, demand can be met by other alternatives such as solar, wind or burning fossil fuels. However, the plants are the best option because it is already a consolidated technology and in greater concentration.

With the turbines, Q_1 and Q_2, operating in parallel in the first three months of the year, the use of floods will be greater. After this period, Q_1 it will operate alone for the next three months, when the flow of the Igarapé is less than its value, it will be turned off and the plant will only operate Q_2 for the remainder of the year. Making the best use of available flows. The same system can be successfully implemented in several areas of the Amazon region or similar. Currently, numerous bridges in the region are in the same state of deterioration and in need of imminent replacement, where the possibility of implementing this project can be evaluated.

5. ACKNOWLEDGEMENTS

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